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EVALUATION OF THE IMPACT OF FATTY ACID METHYL ESTER (FAME) CONTAMINATION ON THE THERMAL STABILITY OF JET A

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Interim Report

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14. ABSTRACT
Current specifications for Jet A limit the amount of FAME contamination to 5 ppm (5 mg/Kg). The focus of this work was to evaluate the thermal stability impact to Jet A due to FAME contamination at levels up to 400 ppm (400 mg/Kg), the goal being to provide data that supports increasing the level of allowable FAME contamination in Jet A from 5 ppm to 100 ppm. Testing was performed by the U.S. Air Force at the Air Force Research Laboratory, Fuels and Energy Branch using the Advanced Reduced Scale Fuel System Simulator (ARSFSS). Results of testing showed that at 400 ppm contamination, there was no definitely discernible negative impact on thermal stability due to FAME contamination.

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Table of Contents

List of Figures

List of Tables

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- EI-JIP for provision of the fuel necessary for this program.

List of Acronyms

Acronym	Definition
AFHX	Airframe Heat Exchanger
AFPA	Air Force Petroleum Agency's Wright-Patterson Aerospace Fuels Laboratory
AFRL	Air Force Research Laboratory
AFTSTU	Aviation Fuel Thermal Stability Test Unit
ARSFSS	Advanced Reduced Scale Fuel System Simulator
B100	100% Bio-based Diesel Fuel
BFA	Burner Feed Arm
CAA	Civil Aviation Authority
DP	Differential Pressure
EDTST	Extended Duration Thermal Stability Test
EHSV	Electro-Hydraulic Servo Valve
EI-JIP	Energy Institute - Joint Industry Project
FAME	Fatty Acid Methyl Ester
FCOC	Fuel-Cooled-Oil-Cooler
FDV	Flow Divider Valve
GC/MS	Ga Chromatograph/Mass Spectrometer
GDTC	Generic Durability Test Cycle
GPH or gph	Gallons Per Hour
HP Pump	High Pressure Pump
HT	High Temperature
JFTOT	Jet Fuel Thermal Oxidation Tester
JIG	Joint Industry Group
Kg or kg	Kilograms
LDSF	Long Duration Switched Fuel
LT	Low Temperature
mg	milligrams
MT	Moderate Temperature
OEM	Original Equipment Manufacturer
PPH or pph	Pounds per Hour
PPM or ppm	Parts Per Million
PW	Pratt & Whitney
QCM	Quartz Crystal Microbalance
RPM	Revolutions Per Minute
RQTF	Fuels and Energy Branch, AFRL
SV	Servo Valve
UK	United Kingdom
WWT	Wetted Wall Temperature

1.0 EXECUTIVE SUMMARY

Current ASTM D1655/Defense Standard 91-91specifications for Jet A/A-1 limit the amount of FAME contamination to less than 5 ppm (5 mg/Kg). This limit has been adopted by the Aviation Industry as an interim measure due to the possible risk of trace FAME affecting the rate of deposit formation in aircraft fuel/engine systems. The focus of the work presented in this report was to evaluate the thermal stability/deposit formation tendency due to FAME contamination at levels up to 400 ppm (400mg/Kg) in Jet A – the goal being to provide data assessing the impact of increasing the level of allowable FAME contamination in Jet A/A-1 from less than 5 ppm to less than 100 ppm.

Testing was performed by the University of Dayton Research Institute (UDRI) and the U.S. Air Force at the Air Force Research Laboratory (AFRL), Fuels and Energy Branch and was accomplished on a single FAME-sensitive fuel using bench scale (JFTOT® and QCM) test devices as well as the Advanced Reduced Scale Fuel System Simulator (ARSFSS using three different test method/simulation protocols. While some differences were observed between baseline and FAME-contaminated fuels at the highest test temperatures, such variations could have been impacted by an observed degradation in the overall thermal stability characteristics of the baseline fuel than to the FAME contamination. Also, the variations seen in the data are believed to be within the variance experience that is typical for testing accomplished using these devices and rig.

Therefore this report concludes that, in the variety of measurements, test data and visual assessments <u>taken as a whole</u>, there appears to be no overall substantial indication that FAME contamination in fuel up to 400 ppm causes any significant increase in coke deposition in a variety of engine hardware components. Further, the data does not indicate that there is any substantial degradation in performance or functionality of these components that would lead to service life or maintenance issues.

To substantiate the claim in this report that “the variations seen in the data are believed to be within the variance experience that is typical for testing accomplished using these devices and rig,” the Energy Institute (EI) undertook a limited statistical analysis of two of the parameters measured by the ARSFSS – carbon deposition in the Burner Feed Arm (BFA) and carbon deposition in the Fuel-Cooled-Oil-Cooler (FCOC). The letter report prepared from this statistical analysis by Alisdair Clark on behalf of the EI-JIP is being published as a part of the Final Report from Energy Institute, Joint Industry Program project seeking original equipment manufacturer (OEM) approval for 100 mg/Kg of fatty acid methyl ester (FAME) in aviation turbine fuel.

This letter report concluded that for the low and medium temperature test conditions (LT and MT), all the base fuel and base fuel + 400 ppm FAME deposits were within the repeatability of the test. The report further concluded that for the high temperature (HT) test condition, the base fuel and base fuel + 400 ppm FAME deposits were within the repeatability of the test with the exception of Runs 99 and 102 where the BFA deposits were outside test repeatability and greater than the three base fuel cases and Run 102 where one FCOC deposit was outside test repeatability and greater than the base fuel in one case. These statistical findings reinforce the conclusions of this report.

In conclusion, testing in this program does not indicate that the performance, operability or longevity of aircraft fuel systems and engine is adversely impacted through exposure of these components to FAME-contaminated fuel at up to 400 ppm. Therefore, it is even less likely that any adverse impact from FAME-contaminated fuel would be seen at 100 ppm. Therefore the presence of up to 100 ppm FAME contamination in even ‘FAME-Sensitive’ fuels may be expected to have a relatively benign impact on aircraft systems overall with regard to thermal stability. However, in light of some of the data observed in this program, it would be wise to periodically monitor for FAME contamination in fuels where the inherent thermal stability of the fuel is suspect or a known issue as this contamination might exacerbate coking and deposition under these conditions.

2.0 INTRODUCTION AND BACKGROUND

Bio-derived components are being used more widely in diesel fuel as world governments mandate use of sustainable sources in transportation fuels to mitigate CO_2 impact and reduce dependency on crude oil. These 'bio' components are mainly a family of chemicals known as fatty acid methyl esters"(FAME). Distribution of diesel containing these bio-components has been and will continue to be through trucks and pipelines – the same transportation methods used to transport other transportation fuels – including jet fuels.

FAME is a surface-active material, meaning that it can adhere to pipeline and truck tank walls. As a result of this adherence, FAME can become a contaminant in other non-biodiesel fuels as it is released off the pipeline or truck tank walls and into other products during transport. In addition, small amounts of FAME can remain within distribution manifolds, transfer points, pipes, tanks and vehicles. At high enough concentrations, FAME may adversely impact fuel characteristics in several ways. Thermal stability can be adversely affected resulting in more engine maintenance. FAME contamination may also damage elastomer seals resulting in cracking or softening of seal materials. FAME-contaminated fuels can be more corrosive and can raise the fuel's freezing point - which can, in extreme cases, result in 'gelling' of the fuel under certain low-temperature conditions. The presence of FAME may also result in a higher fuel water content and therefore an increased risk of microbial contamination.

In response to these concerns, the aviation fuel community (aircraft and engine OEMs and aviation fuel producers) has approved the use of aviation fuel containing less than 5 ppm (5 mg/kg) of FAME through the ASTM D1655 and DEF STAN 91-91 fuel specification. However, this low contamination limit poses significant operational challenges to pipeline operators as governments mandate higher and higher levels of FAME in diesel fuels. In Joint Inspection Group (JIG) Bulletin Number 15, November 2007, the JIG Product Quality (PQ) Committee stated "*Renewable transport fuels legislation around the world is already making an impact on the operation of bulk fuel transport systems and it will likely become of greater significance from early in 2008. Therefore, the JIG PQ committee believes that maintaining procedures that hold trace levels of FAME to the current minimum level of detection (5ppm) are not operationally practical or sustainable in the longer term. The industry needs to establish what level FAME in jet fuel affects its suitability for use…the initial test results provide some confidence that trace levels of FAME up to 100 ppm may be acceptable*."

As the world-wide increase in use of bio-fuels increases and the higher levels of FAME in these fuels are mandated, the likelihood that aircraft operators will more frequently experience FAME contamination in jet fuel above the current 5 mg/kg (5ppm) limit (ASTM D1655/DEF STAN 91-91) is high. In anticipation, aircraft engine and airframe OEMs have agreed that up to 30 ppm FAME contamination in jet fuel may be permitted subject to certain strict limitations. The Civil Aviation Authority (CAA) has developed guidelines for aircraft operation with FAME-contaminated fuels as guidance for aircraft operators. These recommended guidelines are shown in Table 1 and are an indication of the serious concern surrounding FAME contamination of jet fuel.

Table 1 – CAA Recommended Operations Limitations for FAME-Contaminated Fuels[1]

Limitations for Operation with Aviation Turbine Fuel Containing FAME					
FAME Level	**Limitations[1]**				**Comments**
	Aircraft en-route	**Engines operated on the ground**	**Aircraft on ground (engines not yet operated)**	**Aircraft waiting to be fueled**	
Less than 5 ppm	None	None	None	None	Level within specification criteria
5 ppm to 30 ppm	Two uplifts[2] of fuel containing FAME	Two uplifts of fuel containing FAME	Allow dispatch. Two uplifts of fuel containing FAME	Fuel aircraft and allow dispatch. Two uplifts of fuel containing FAME	Contact aircraft and engine manufacturer to determine subsequent maintenance actions
Greater than 30 ppm	Divert immediately to suitable airport	Do not allow dispatch	Do not start aircraft or allow dispatch. Take action to ensure fuel in aircraft tanks is below 30 ppm FAME then apply requirements as defined for 5 ppm to 30 ppm	Do not fuel aircraft. Take action to ensure fuel supply to aircraft is below 30 ppm FAME then apply requirements as defined for 5 ppm to 30 ppm	Contact aircraft and engine manufacturer to determine subsequent maintenance actions

[1] Based on operational status of aircraft at time of discovery of contamination.
[2] An uplift is defined as the transferring of fuel from a ground-based fuelling facility or vehicle to the aircraft fuel tanks.

According to ASTM D4054, in order to assess the impact of contamination or additives, testing of that contamination or additive must be accomplished at 4 times (4X) the proposed or sought allowable maximum contamination level or concentration. Therefore, if it is desired to raise the allowable FAME level in jet fuel from 5 ppm to 100 ppm, testing of FAME-contaminated (FC) jet fuel to a level of 400 ppm (400 mg/kg) must be undertaken. Testing at this level was recently accomplished by Rolls-Royce (UK) using their Aviation Fuel Thermal Stability Test Unit (AFTSTU) located at The University of Sheffield[2]. In a report released in November 2011 authors generally concluded that there was a significant and repeatable degradation in fuel thermal stability for fuel contaminated with FAME. In addition to the increased deposition that is present as a result of FAME contamination, this degradation seemed to appear earlier in the test indicating a significant detrimental effect of FAME contamination.

[1] *"Jet Fuel Containing Fatty Acid Methyl Ester (FAME)", Civil Aviation Authority Information Notice, Number IN-2012-116 Issued 16 July 2012*
[2] *"AFTS Test Report: Fame Programme", University of Sheffield, Department of Mechanical Engineering, Blakey, S.G., Chung, W., Wilson, C.W., Report Number R131416, November 2011*

However, there has been some discussion indicating that the operational test parameters used in AFTSTU testing might be too severe and that this severity might be conveying a more negative picture of FAME contamination than reality. In the absence of a clear cut assessment of this FAME-contamination question, AFRL/RQTF was asked to perform similar testing using the Advanced Reduced Scale Fuel System Simulator (ARSFSS).

The ARSFSS is functionally similar to the Rolls-Royce/Sheffield AFTSTU and has been used in many programs including the Air Force's Alternate Jet Fuel Program and various fuel additive evaluations such as pipeline drag reducer and thermal stability additive evaluations. Where the AFTSTU simulates 10,000 to 20,000 operational hours within 300 hours of rig running, these hours are at temperatures in excess of real-world aircraft fuel system conditions as the AFTSTU attempts the proverbial time-for-temperature trade-off to accelerate analysis for a general representation of engine service life. When exercising a time-for-temperature trade-off, there is risk that the higher temperatures used can invoke compromise in simulation integrity by initiating chemistries that might not otherwise occur in a real aircraft at real-world conditions. Even so, it is possible, with enough testing and experience, to develop a solid understanding of how results, even at non real-world conditions, can be used to predict real-world experience.

On the other hand, the ARSFSS operational test conditions are derived from and representative of fuel system conditions present in advanced <u>military</u> aircraft fuel systems and therefore represent less of an attempt at the time-for-temperature trade-off. This does not necessarily mean that one hour of ARSFSS operation is equivalent to one hour of real-world aircraft/engine operation as such a correlation has never been evaluated or claimed. In addition, the configuration of the ARSFSS includes implementation of fuel recirculation (See Figure 3) which is considered by AFRL to be vital to the correct assessment of how a fuel behaves since time at temperature history is critical. The ARSFSS is also operated using 'mission' cycles where each mission is a roughly two-hour implementation of the basic elements of a typical mission – including but not limited to elements such as Engine Start, Ground Idle, Take-off, Cruise, Idle Descent, Landing, Taxi and Engine Shutdown. A complete ARSFSS run will typically consist of between 65 and 150 of these mission cycles. By operating the ARSFSS in this mission cycle mode, the test takes into consideration the time/temperature history that fuel experiences in real aircraft systems. All of these test features make the ARSFSS a very realistic thermal stability test.

The fundamental tenets of this test plan were based on past ARSFSS experience coupled with the outcome of many discussions amongst the EI-JIP FAME Contamination Team. These discussions were used to establish operational test procedures and conditions for the evaluation of the thermal stability impact of FAME contamination in jet fuel, based on variances on the typical AFRL operations scenario for the ARSFSS.

Prior research accomplished in the area of FAME contamination of jet fuels has indicated that certain fuels may exhibit sensitivity to such contamination. Since such a fuel would obviously pose a more significant risk to fuel system operations, especially for advanced systems, a FAME-sensitive (FS) fuel was used for the program.

More detailed information regarding the FAME material and the test fuel is given in Sections 4.1.1 and 4.1.2.

3.0 PROGRAM GOALS AND OBJECTIVES

The overall objective of this program was to determine if FAME contamination levels of up to 100 ppm would be acceptable for aircraft use. Therefore testing was accomplished at a level of 400 ppm FAME contamination as prescribed by ASTM D4054. The logic is that if no adverse impact of 400 ppm FAME is observed, then it can be safely assumed that the presence of 100 ppm FAME will not result in any negative operational impact on the aircraft caused by the fuel – particularly with respect to thermal stability. Use of 400 ppm FAME contamination also represents a severe case to account for certain fuels which may or may not exhibit a particular thermal stability sensitivity to the presence of FAME.

Since prior testing of FAME-contaminated fuel in several other test devices and rigs in some cases was unable, for various reasons, to produce data that offered "consistent differentiation between baseline and FAME-doped fuel"[3], the EI-JIP elected to solicit the U.S. Air Force, AFRL to operate its ARSFSS with the goal of "creat[ing] an additional data point based on a rig of similar sophistication and design philosophy" [4] to augment the findings of the University of Sheffield using the AFTSTU rig. The assumption being that such testing in the ARSFSS would allow testing to be accomplished on a different baseline fuel under simulated mission cycle testing that would be more directly comparable to real-world aircraft operations. It was hoped that such data would also possibly shed some light on some of the inconsistent results obtained in prior testing.

In addition to evaluating the impact of FAME contamination, it was desired to operate the ARSFSS at similar conditions to the AFTSTU so that the 'read across' between AFRL's ARSFSS rig and University of Sheffield's AFTSTU rig might be obtained. Such read-across will be useful to have not only for this program but for any potential future collaboration programs.

[3] *"Aviation fuels Customer Report: Joint Industry Programme for 100 ppm FAME Approval", Report Number SR.12.10491, Shell Global Solutions (UK), Shell Technology Centre Thornton, England, February 2012.*

4 "Aviation fuels Customer Report: Joint Industry Programme for 100 ppm FAME Approval", Report Number SR.12.10491, Shell Global Solutions (UK), Shell Technology Centre Thornton, England, February 2012

4.0 Experimental

4.1 Materials

4.1.1 FAME

A mixture of FAME was used for this program and was provided by Chevron as a B100 material with a flash point of 266 °F (130 °C). Five gallons of this material was received by AFRL for use in this program. The material as received was a four-component blend, with equal volumes of soy, rape seed, palm, and tallow oil FAMEs. Upon receipt by AFRL, this material was given an ID code of **POSF-8586**. This material was used throughout all testing in this program to prepare FAME-contaminated fuels. The thermal stability breakpoint of the FAME material itself was not determined.

4.1.2 Baseline Fuel and Fuel Blends

The baseline fuel for this program was provided by EI-JIP and was a wet-treated, not hydroprocessed, Jet A fuel from a major gulf coast refinery with a manufacture sample ID of 2527284. To the best of the information available, no antioxidant was used in the fuel. The fuel arrived at WPAFB in three truck-loads on three separate days as shown in Table 2. The fuel was offloaded into a 25,000-gallon underground tank on the S-Farm (Tank S-8) and remained in that tank for the duration of the program.

Table 2 - Shippment of Jet A Baseline Fuel

Truck No.	Date	Quantity Off-loaded
1	**18 Sep 12**	**6,927 Gallons**
2	**19 Sep 12**	**6,867 Gallons**
3	**21 Sep 12**	**6,880 Gallons**
TOTAL GALLONS REC'D		**20,674 Gallons**

Upon receipt, samples of the composited fuel were removed from Tank S-8 and provided to AFPA/PTPLA for a full specification test workup. The fuel fully met ASTM D1655 Jet A/A-1 specifications and results of this initial testing are provided in Appendix A. This fuel was assigned an ID of POSF-9326

The ARSFSS rig operates using fairly large quantities of fuel so it is directly plumbed to three dedicated tanks on the S-Farm. Tanks S-3 and S-4 are 1,000-gallon tanks while S-15 is a 6,000-gallon tank. Since each ARSFSS run was anticipated to take a full 900 gallons of fuel, Tanks S-3 and S-4 were dedicated to ARSFSS use – with S-3 being allocated to hold only baseline fuel and S-4 to be used for FAME-contaminated fuel. In preparation of FAME-contaminated fuel for the program, a measured amount of FAME material was added to the S-4 tank while it was being filled with baseline fuel. Upon filling with the required amount of baseline fuel, the fuel in the tank was recirculated for 2 hours to ensure proper mixing. After recirculation, samples of the FAME-contaminate fuel were taken and analyzed for the proper FAME contamination level. The target was 400 ppm +/- 5 ppm. If the proper concentration was not achieved, additional FAME or baseline fuel was added and recirculated until target goals were met. For the duration of the program FAME contamination levels for all 'contaminated' fuels never varied from this 400+/-5 ppm target.

4.2 Fuel Testing

4.2.1 Quantifying the Amount of FAME in the Fuel (Linda Shafer, UDRI)

Quantifying the amount of FAME in the test fuels was performed via the use of an Agilent 7890/5975 gas chromatograph/ mass spectrometer (GC/MS). The GC column was a 30-meter DB-5MS capillary column (0.25 mm ID and 0.25 µm film). The GC temperature program employed an initial temperature of 40 °C (0.5-minute hold) followed by ramping (20 °C/min) to 300 °C (5-minute hold). A constant column flow rate of 1 mL/min, and 20:1 split 1-uL injections were used. The GC injector temperature was 275°C, and the Agilent Model 5975 mass spectrometer transfer line was held at a temperature of 280°C. The mass selective detector was operated in selected ion monitoring mode (SIM), and was only turned on where the compounds of interest eluted to protect the detector from the high concentrations of other fuel components. Mass spectral data was recorded for characteristic masses of the compounds of interest (i.e., 74, 67, and 55 for palmitic, linoleic, oleic, and stearic acid methyl esters; and 85 for the tetracosane internal standard).

A minimum of four standard solutions containing FAME and the internal standard (tetracosane – $C_{24}H_{50}$) were prepared in FAME-free Jet A (POSF-9326) fuel diluted at the same ratio in hexanes as the samples (1 to 5) and analyzed. The standard concentrations at 320, 360, 400, and 440 ppm, rather narrowly bracketed the expected sample concentration in order to more accurately quantify in the target concentration range of 390 to 410 ppm. The instrument was calibrated from the extracted ion area responses obtained for the four major FAME components and internal standard at each calibration level. A separate calibration was performed for FAME at low concentrations (5 to 40 ppm). Samples of fuel were diluted 1 to 5 with hexanes and the tetracosane internal standard was added. The FAME concentration in each sample was quantified using the extracted ion responses for the four FAME components, and tetracosane in the sample. The accuracy of the method was approximately ± 5 ppm at the 400 ppm level. At least one standard was run with each batch of samples to verify the calibration. A new calibration was required if the standards were not within 6 ppm of the true concentration.

4.2.2 Quartz Crystal Microbalance (Zach West, UDRI)

In preparation for ARSFSS testing, baseline and FAME contaminated fuels were subjected to standard Quarts Crystal Microbalance (QCM) evaluation.

Thermal stability characteristics of the baseline Jet A fuel (POSF-9326), with and without the addition of 400 mg/kg of a FAME mixture (POSF-8565), was assessed using a Quartz Crystal Microbalance (QCM) apparatus. The experiment was conducted by placing 60 mL of the fuel sample to be evaluated into a batch reactor. The sample was air saturated under room conditions, then closed and heated to 140 °C. Measurements of headspace oxygen, temperature, pressure, and mass accumulation were recorded, while the sample was reacted isothermally for 15 hours. The objective was to investigate the oxidation and mass deposition characteristics of the experimental samples under typical QCM conditions in an effort to identify any differences in thermal stability behavior with the addition of FAME impurity.

Figure 1 shows the headspace oxygen and mass accumulation profiles for the Jet A and Jet A + FAME fuel samples for two different time periods. For the time period covering the receipt and acceptance of the baseline fuel and the formulation of initial samples of FAME-contaminated fuels (September 2012), the data shows that the Jet A fuel is a slow oxidizing fuel under these conditions and does not consume all of the oxygen – even after 15 hours of stress duration. Conversely, the FAME-contaminated fuel sample exhibits a rapid consumption of oxygen within the first 4 hours of stress duration. The Jet A and Jet A + FAME samples appear to have similar deposition rates for the first ~2.5

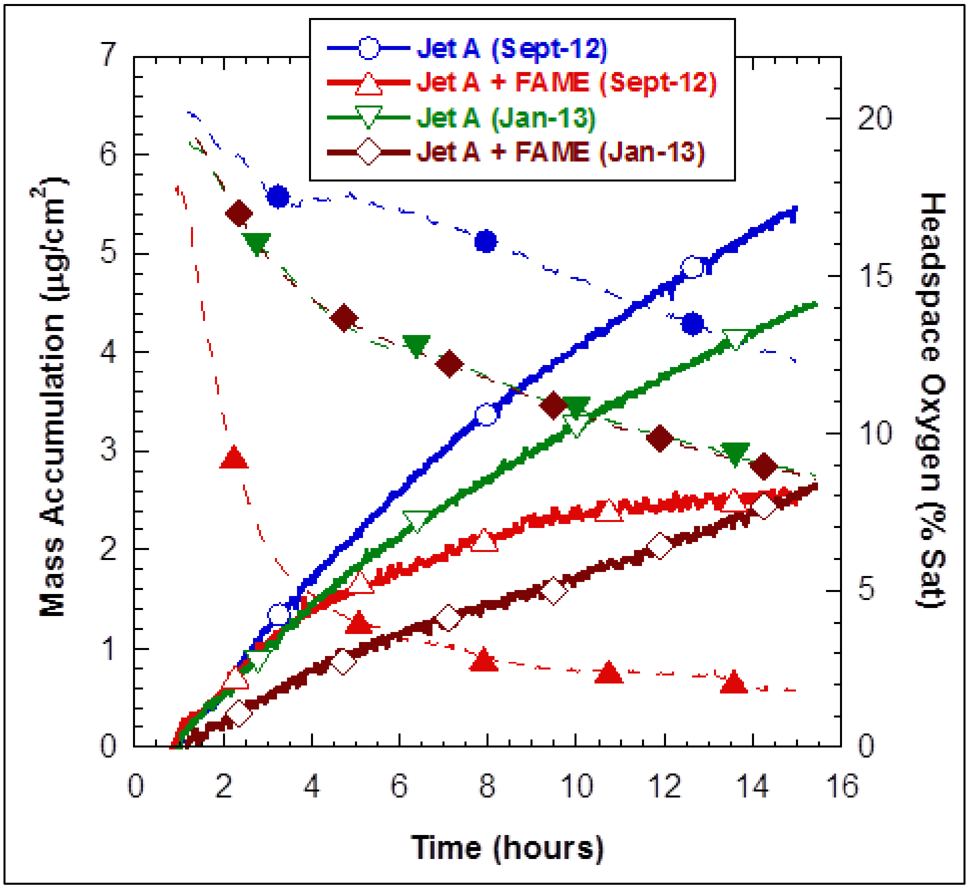


Figure 1- QCM Results on Baseline and Contaminated Fuel

hours, until significant oxygen depletion in the Jet A + FAME sample causes a decline in the deposition rate for that fuel. The Jet A fuel gives 5.5 µg/cm^2 of deposit after 15 hours of stress, which is a moderate-to-high amount of deposits compared to known JP-8 and Jet A fuels (typical range is ≤ 6 µg/cm^2). Both of these samples appear to exhibit moderate thermal stability characteristics.

For the second time period featuring samples taken towards the end of the test program (January 2013), both the Jet A and Jet A+FAME samples exhibited similar rates of oxygen consumption. However, as in the earlier tests, the Jet A+FAME sample again showed a decline in the deposition rate compare to the base fuel.

In summary, FAME addition to the Jet A fuel (POSF-9326) shows some contradictory behavior, i.e., the FAME impurity increased the base fuel oxidation rate but decreased the surface deposit amount after 15 hours of thermal stress. Since the QCM is a closed system (once the oxygen has been consumed, oxidation reactions stop) and aircraft fuel system designs do not stress fuels to the point of complete oxygen consumption, the increased oxidation rate caused by the FAME impurity may have a negative impact on the measured thermal stability of the fuel at low extents of oxidation.

4.2.3 *JFTOT® and Breakpoint Testing*

JFTOT testing was also performed on the as-received fuel (composited) as well as periodically through the program. Initially, the Breakpoint for the baseline composited fuel was determined to be 285 °C. However, as the program progressed, periodic rechecks indicated that the JFTOT® Breakpoint had deteriorated to 275 °C. This will be further discussed in Section 5.1.

4.2.4 *Oxygen Measurements*

In the initial preparation of the test plan for this program, it was conceived that making dissolved oxygen measurements in the fuel might be useful in understanding the impact of FAME contamination on thermal deposition behavior. A single dissolved oxygen sensor (Mettler Toledo, InPro 6800 oxygen sensor with a 4100e transmitter) was installed on the ARSFSS (Figure 2). Four tap points were installed on the ARSFSS so that dissolved oxygen measurements could be made at all four locations – thereby allowing tracking of oxygen consumption through the rig. Figure 4 shows a schematic of the ARSFSS indicating the tap points (blue circles) for dissolved oxygen measurements. Oxygen levels after the burner feed arm were >= 95% relative saturation for most cases; therefore, the total amount of oxygen consumed was very little (< 5% or < 4 ppm consumed). Therefore, there does not appear to be a significant difference between the consumption levels of neat Jet A and the Jet A with FAME cases (at least within the uncertainty of the O_2 sensors used, which is about +/- 2% absolute). Also, this is a very low amount of total oxygen consumption.

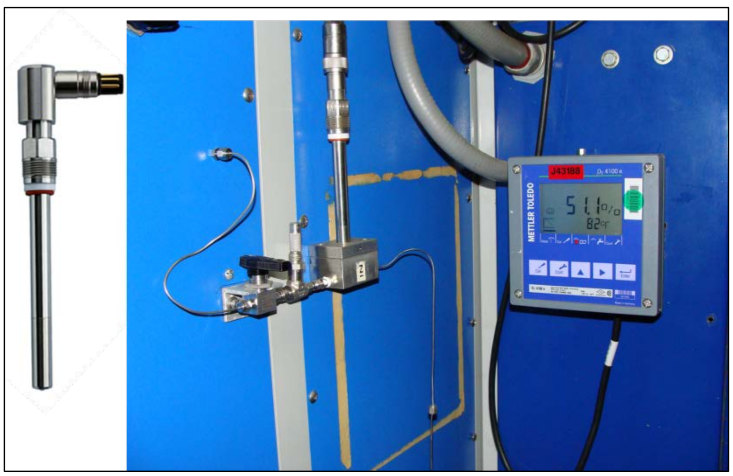


Figure 2 – Dissolved Oxygen Sensor and Placement Location on the ARSFSS
Left - Sensor as Uninstalled
Right – Sensor as Installed

4.3 Mission Cycle Testing and ARSFSS Operations

4.3.1 *General ARSFSS Description and Operations*

The Advanced Reduced Scale Fuel System Simulator (ARSFSS) is a thermal stability evaluation device that more closely represents and replicates military aircraft fuel system operating conditions than any other sub-aircraft scale test device in the world. Designed as a joint effort between AFRL, Boeing and Rolls Royce (UK) in the mid-1980s, the ARSFSS has been used extensively to evaluate fuels and additives under realistic aircraft fuel system conditions for almost three decades. The ARSFSS is used by AFRL as the last test before releasing a fuel or additive for engine- and component-scale testing and evaluation, or for use in the field. Not only is the ARSFSS capable of realistically simulating the flow, temperature, pressure and residence time profiles for a real aircraft fuel system, but it is capable of imposing these conditions on system hardware in real time with changes to flow, pressure and temperature conditions following a pre-established mission profile. In this way, the ARSFSS can ‘fly’ missions sequentially over time. An ARSFSS test run typically consists of between 65 and 150 missions executed sequentially operating 24 hours per day, 7 days a week. The ARSFSS control system is sophisticated enough to allow the test to operate unattended for days at a time.

The ARSFSS rig itself consists of three major subsystems

- A Fuel Conditioning System
- An Airframe Fuel System Simulator
- An Engine Fuel System Simulator

Figure 3 - Conditioning Tank (left) and Wing Tank (right) on the ARSFSS

A schematic of the ARSFSS is shown in Figure 4. Figure 3 shows the Conditioning and Wing Tanks which comprise the fuel conditioning system and part of the airframe simulator. Figure 5 shows the Body Tank which is also part of the Airframe Simulator. Figure 6 shows the Environmental Chamber, which is also part of the Airframe Simulator and is where heat loads associated with environmental systems and other airframe subsystems are imposed upon the fuel. This chamber is represented by the 'Airframe Heat Loads' element in the Figure 4 schematic. The remaining elements of the ARSFSS are all encompassed in the Engine Simulator. A front view of the Engine Simulator cabinet is shown in Figure 7.

The ARSFSS test rig is modifiable so that many different fuel system configurations and many different aircraft systems can be simulated. For this program, the ARSFSS was configured to simulate an advanced aircraft with an advanced engine. Rig scaling is based on 1/3 scale of a single nozzle – making the ARSFSS scaled overall at 1/72nd scale of the advanced engine. Total fuel required for each ARSFSS test is between 900 and 1,500 gallons – depending on the mission profile used for the testing. For this program, a modified Generic Durability Test Cycle (GDTC) mission profile was used. Sixty-five mission cycles were executed for each test run requiring approximately 900 gallons of fuel – with one test extending to 204 mission cycles.

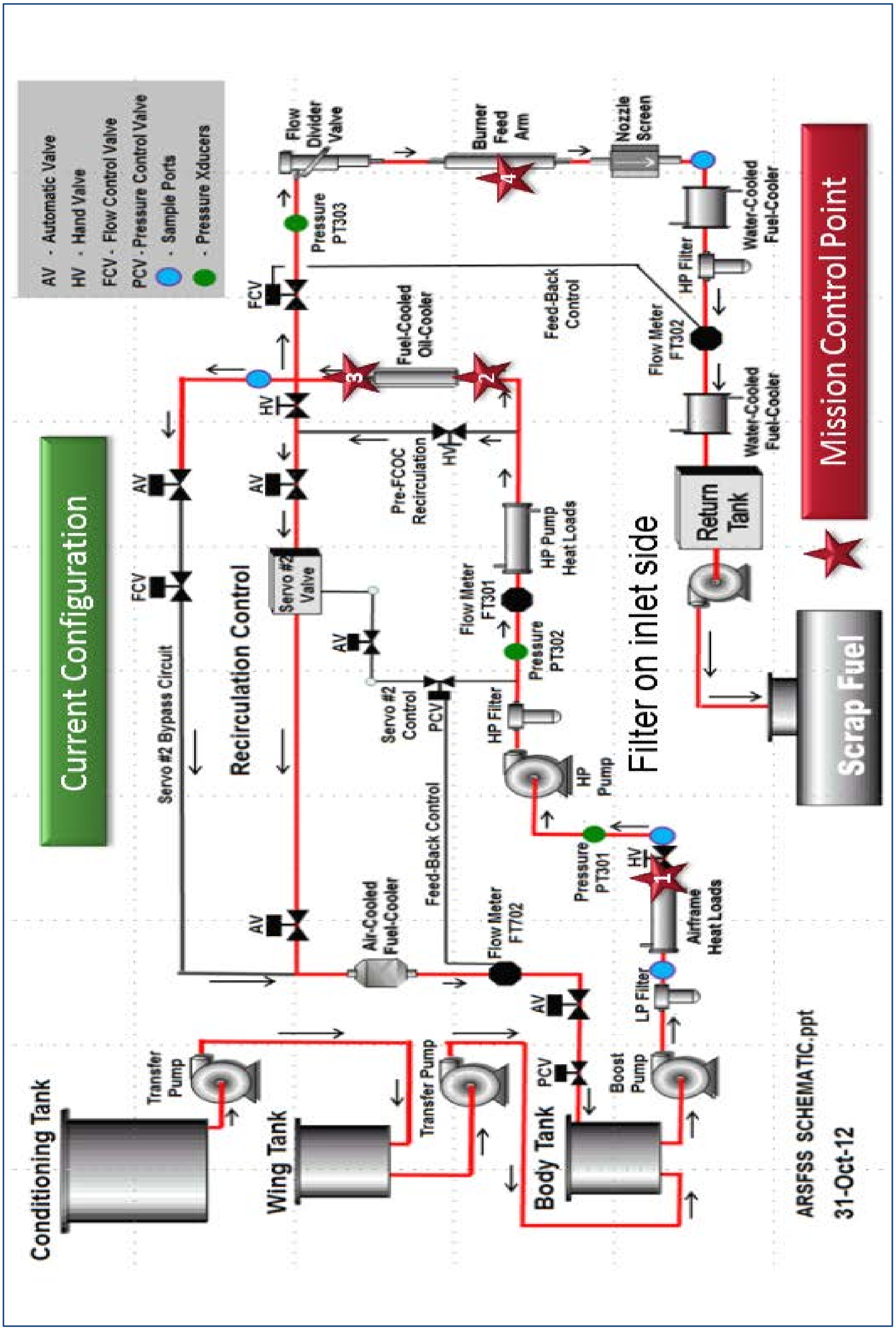


Figure 4 – Schematic of ARSFSS Showing Dissolved O2 Measurement Taps and Control Points

Figure 5- Body Tank

Figure 6 – Environmental Chamber for Simulation of Airframe Heat Loads

Key data elements from the ARSFSS consist of both qualitative and quantitative information. The key comparison points for the ARSFSS are the fuel's behavior in the Servo Valve, Flow Divider Valve, Fuel-Cooled Oil Cooler and Burner Feed Arm. These devices are described in the following sections.

4.3.1.1 Servo Valve (SV)

For the ARSFSS, the Servo Valve component (Figure 8) is the second stage or hydraulic portion of an Electro-Hydraulic Servo Valve (EHSV) commonly found in advanced engines. This particular valve has a diametrical clearance of 0.00010 to 0.00020 inch and a total stroke of +/- 0.032 inch. In an EHSV, the first stage of the control is an electrical servo mechanism that responds to an input current or voltage. Increasing current or voltage results in a small movement of the electrical servo components. The electrical servo components are coupled to a hydraulic component – the second stage of the control of the valve. The hydraulic portion of the valve consists of a spool and sleeve arrangement where a specially designed spool moves within a sleeve. Movement of the spool causes clearances within the spool/sleeve assembly to change and thus, control flow through the valve. Because the hydraulic portion of the valve is driven by pressures within the fuel system, the small forces generated by electrically positioning the electrical-servo portion of the valve are amplified by system hydraulic pressures resulting in a substantial moving force being applied to a hydraulic component. These combined electrical and hydraulic components give engine manufactures the ability to exert substantial hydraulic forces upon the fuel system control using small electrical forces.

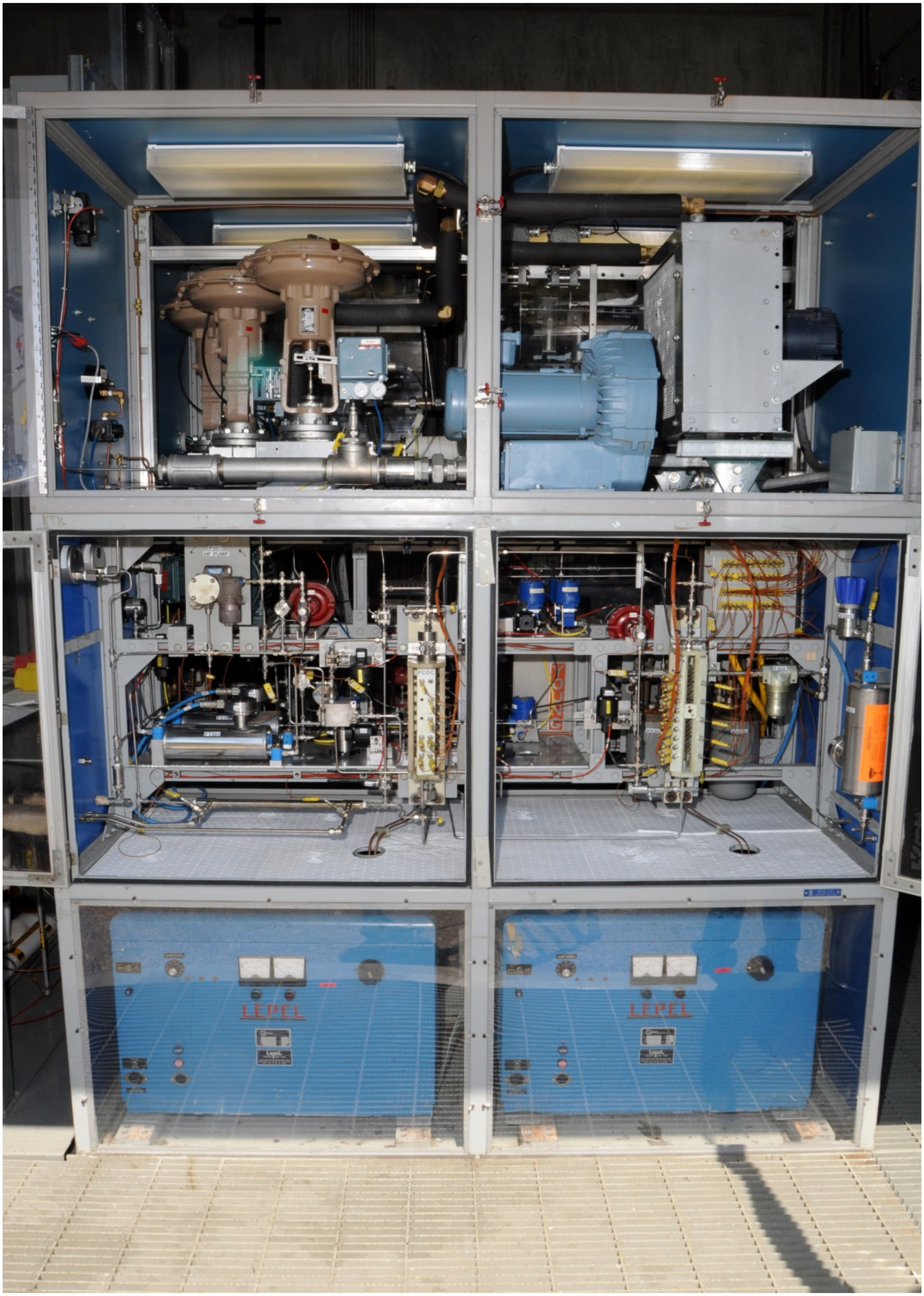


Figure 7 – Engine Simulator Cabinet

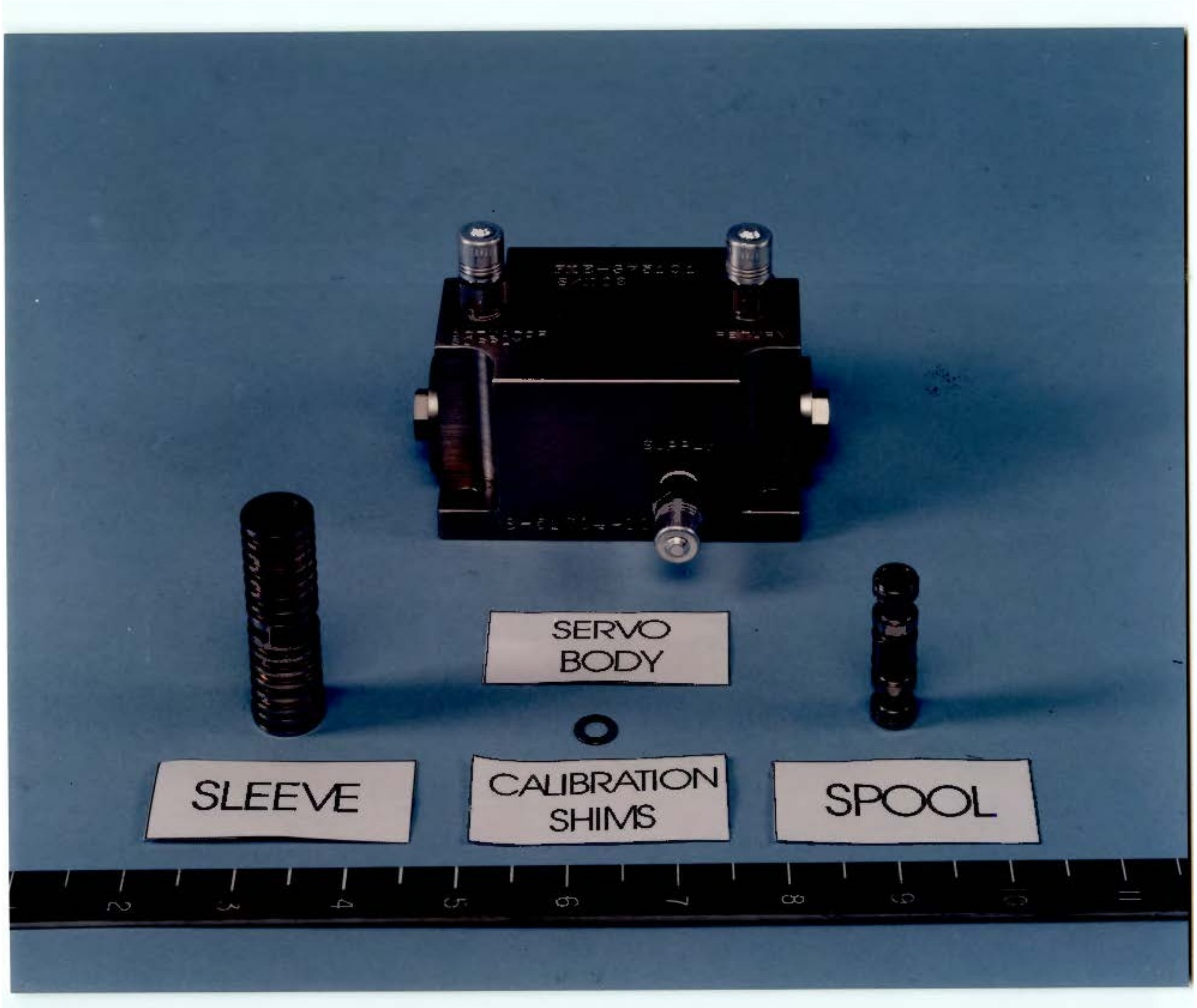


Figure 8 - Servo Valve Components and Assembly

However, since the hydraulic portion of the valve sees the fuel flow at bulk fuel system temperatures, coking and fouling can occur in these components. Since the ability of the EHSV to regulate fuel flow is dependent upon the unrestricted movement of the spool and sleeve valves that make up the hydraulic portion of the valve, even the slightest amount of deposition occurring in this valve can impact valve performance by causing hysteresis in the valve. Hysteresis in a valve can basically be described as the tendency of the performance of the valve (in terms of valve flow and pressure) to be dependent on its previous position along with whether the change in pressure to cause a change in valve flow is increasing or decreasing when reacting to an external control signal. Hysteresis leads to varying degrees of inaccuracy relative to valve actuation and operating forces and can drastically affect the performance of an engine fuel system. Under the best of circumstances, a well-designed and well-functioning control valve has little or no hysteresis thereby allowing the control algorithms that predict and impose control movements to reliably and predictably position the valve for stable system control. As hysteresis increases, control algorithms may not properly compensate and system control can become unstable.

For all ARSFSS testing, SV hysteresis is measure pre- and post-test and is defined by relating differential pressure (DP) across the SV to flow rate (F) through the valve. To generate this SV Differential Pressure (DP) vs. Flow data curve, the ARSFSS HP Engine Pump is operated at a fixed high

RPM to generate fuel pressures necessary to actuate the SV. Fuel flow from the pump is regulated by a control valve (FCV801) starting with the control valve set to about 75 percent which applies pressure to the SV and forces it to a 'closed' position. Since the SV is not a shut-off valve, there is usually some small measure of flow through the valve. With FCV801 at 75% (SV essentially closed), a flow measurement is made once it is determined that the flow through the valve is stabilized. Once that measurement is taken, FCV801 is set to 70% open and another measurement of flow is made. This stepwise closing of FCV801/opening of the SV continues in 5% increments until the SV is essentially full open (which is about 30% on FCV801). Once the final flow measurement is made at this condition, FCV801 is changed again, in 5% increments until FCV801 is back at the starting position of 75%. Flow measurements are made at each of these incremental positions and the results tabulated.

These measurements are made on the SV as installed in the ARSFSS both pre-test and post-test. The cyclic measurement process is executed a minimum of two and a maximum of three times and the data collected and tabulated. The cyclic measurement process is repeated because it is common for the first sequence of measurements to be 'off' slightly as a result of the valve 'seating' itself and getting fully wetted and lubricated with fuel. The second measurement series tends to be more representative of the SV in operational mode. The third and final series tends to virtually duplicate the second series so it is most times not performed. In the post-test mode, the third series is only performed if there are too many anomalies evident in the first two series because valve movement tends to remove deposition from the valve thereby returning the valve to a near-pre-test condition and thus eliminating the ability to assess the impact of coking on valve performance.

In addition to the hysteresis measurements made on the Servo Valve, at the end of each test run the Servo Valve is disassembled and photographed to document the degree and nature of the fuel deposits inside and on the valve components. This deposition, along with Servo Valve hysteresis measurements, documents the condition of the valve at the end of each test.

The very nature of the EHSV tends to minimize the impact of hysteresis naturally so no firm value for hysteresis in this component has been established as an acceptable amount. Instead, SV performance is generally looked at with a do-no-harm criteria. Post-test SV hysteresis behavior is determined generally to be acceptable as long as the hysteresis is not significantly different from pre-test measurements. This causes the data obtained on the SV performance to be somewhat subjective rather than analytical.

4.3.1.2 Flow Divider Valve (FDV)

Perhaps even more critical than the EHSV, valve hysteresis is a significant issue in the combustor nozzle FDV. The engine simulator part of the ARSFSS was designed around an advanced engine using 24 combustor nozzles. Each of the 24 combustor fuel nozzles for this design contains two fuel flow paths to the injector nozzle – a Primary and a Secondary. The Primary path typically handles fuel flow in the low power or low fuel flow regime – for example, engine starting and ground idle and idle descent and conditions. Once the engine requires fuel flows outside of this 'low flow' regime, a Secondary 'high flow' path is opened up to deliver the necessary flow to the engine. This dividing of the fuel flow is accomplished using a pressure-driven FDV. This valve is physically positioned upstream of the fuel nozzle face and is located outside of the combustor in the compressor bypass or fan air flow path. Since this air flow can reach high temperatures, the FDV is subject to occurrence of coking. As with any other valve that is used to regulate flow, any coking or fouling of the FDV can result in significant valve hysteresis. Unlike the EHSV, the FDV is driven only by inlet fuel pressure and does not have the benefit of multiplied hydraulic forces to overcome hysteresis. Thus, this valve can be quite sensitive to hysteresis brought on by fuel fouling.

In the ARSFSS, an actual FDV from an advanced engine is used. The flow slot has been modified by narrowing its width so that the typical stroke of the valve in the ARSFSS' reduced flow environment is essentially the same as for the full flow in the engine. Figure 9 shows the various components of the FDV as well as an assembly view of the FDV itself.

The normal acceptability criteria for FDV hysteresis would be 7% or less. According to design engineers, hysteresis values beyond 7% could adversely impact the fuel flow to the nozzles and thus

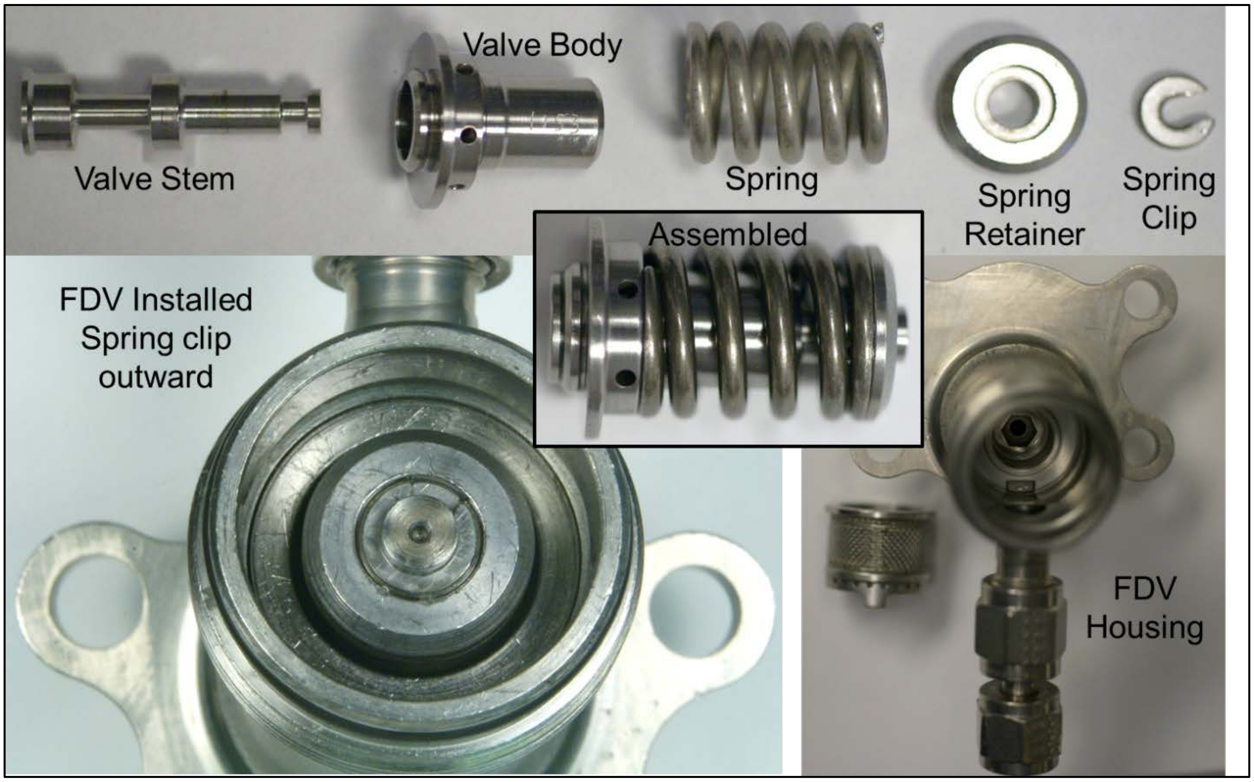


Figure 9 – FDV Components and Assembly Views

change the combustor temperature profile in the engine. An altered combustor temperature profile can have serious and deleterious impact on engine performance, reliability and safety.

Hysteresis measurements on the FDV are determined in much the same was as for the SV. As with the Servo Valve, in addition to determining FDV valve hysteresis, the FDV is disassembled and photographed at the end of each ARSFSS run to document the degree and nature of the deposition that occurred in and on the valve components. These components include the FDV valve body, valve stem and strainer screen that surrounds the entire assembled valve and protects it from large pieces of debris.

4.3.1.3 Fuel-Cooled Oil Cooler (FCOC)

Aircraft fuel is used for cooling as well as propulsion. One area where fuel is used as a cooling medium is in the cooling of engine lubrication oil. In most systems, this involves simply exchanging heat between the engine oil and the fuel in a simple heat exchanger device – an FCOC. Normally, the FCOC is based on a shell-and-tube heat exchanger design where fuel passes through the exchanger on one side of the tube and engine lubrication oil passes on the other side. The number of tubes used in the FCOC depends upon the engine design and the amount of heat dissipation required. Normally, accepted engine design criteria dictates that bulk fuel temperature out of the FCOC should never exceed 325 °F (163 °C) which is the limit for oil operability in the engine. Obviously, at these temperatures, fuel can foul and coke can be deposited on the inside of the tubes of the FCOC. As with any heat exchanger, any fouling, either on the inside or the outside of the tubes, is detrimental to FCOC performance and can result in engine oil temperatures exceeding design limits. In the ARSFSS, the device simulating the engine FCOC is designed with three 3/8-inch diameter 0.035-inch thick walled stainless steel tubes. The tubes are connected via manifolds at either end of the FCOC device so that the fuel sees three complete end-to-end passes within the FCOC before emerging. The tube that is used for the final pass is removed at the end of each test and cut into 2-inch segments. A LECO Carbon Analyzer is used to measure the amount of carbon deposition that has occurred inside this tube. This carbon deposition data is plotted as part of the data for the ARSFSS run. For this reason, no firm quantitative acceptance criteria has been established for this device. Acceptance is based on the deposition for the fuel under test being not more than the deposition for the baseline fuel. Figure 10 shows the FCOC as disassembled and as installed in the ARSFSS rig.

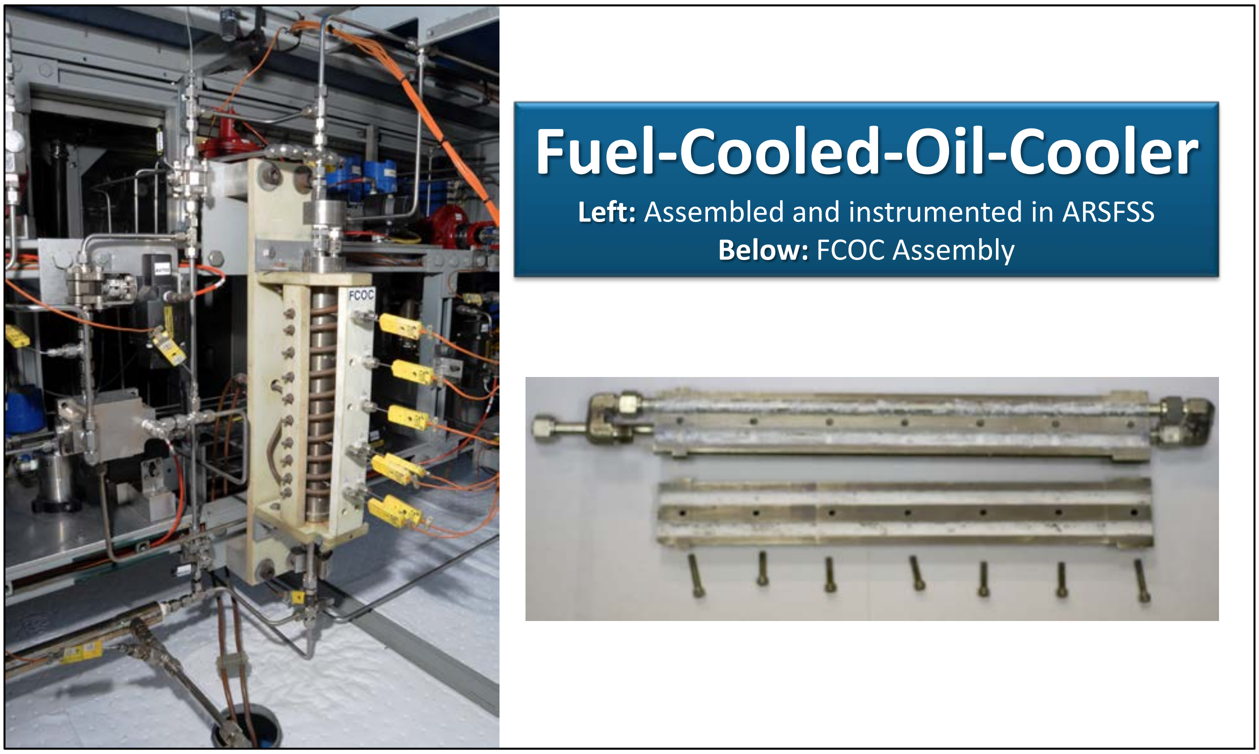


Figure 10 – Fuel-Cooled-Oil-Cooler (FCOC) Installed and Assembly

4.3.1.4 Burner Feed Arm (BFA)

In the engine that was used as a model for the ARSFSS simulator, each combustor nozzle is made up of an assembly of three components – the FDV (which was discussed in a previous Section), the tubular pathways connecting the FDV to the nozzle (often referred to as the burner feed arm (BFA)) and either a pressure-atomizing or air-blast nozzle. The FDV regulates fuel flow to the Primary and Secondary fuel flow paths which transport fuel through the flow tubes (BFAs) to the nozzle. In the actual nozzle assembly, since this portion of the nozzle assembly is subjected to high temperature compressor discharge air, these BFA paths are contained within a complex shroud assembly designed for thermal isolation and protection. As previously described, the performance of the combustor fuel nozzle is critical to engine performance and control. This performance and control is not only impacted by the performance of the FDV in each combustor nozzle assembly, but it is impacted by the ability of the BFA flow paths to deliver unrestricted fuel flow to the nozzle. Significant coke deposits can, however, develop inside these tubes which can restrict fuel flow to the nozzle and therefore impact nozzle assembly overall performance – even though these paths are shrouded for thermal protection.

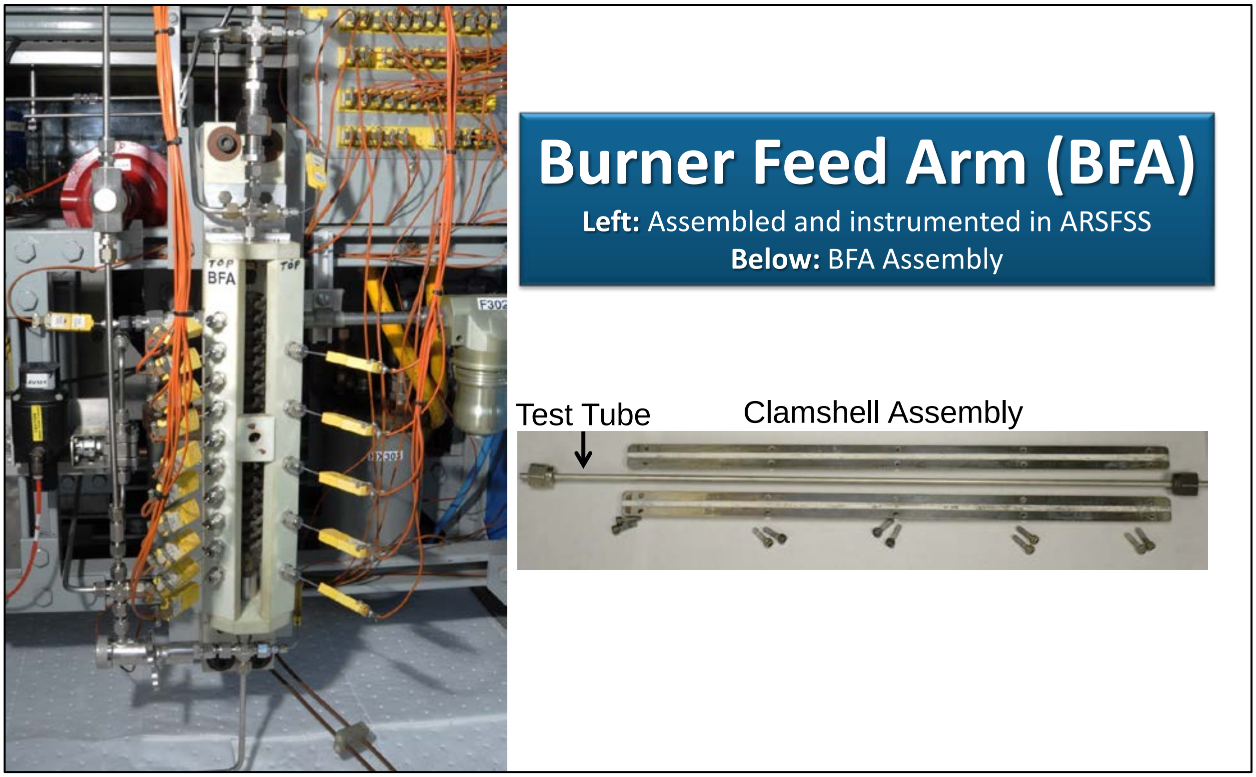


Figure 11- BFA Installed and Assembly

In the ARSFSS, these flow paths are simulated with the Burner Feed Arm (BFA). The BFA is inductively heated and consists of a 1/8-inch, 0.020-inch thick wall stainless steel tube placed in a ½-inch stainless steel clamshell. This clamshell helps evenly distribute the inductively-generated heat along the length of the BFA device. Thermocouples are located on the outside of the 1/8-inch tube along the whole flow path and are used to measure and control the wetted-wall temperature profile. At the end of each run, this 1/8-inch tube is removed and cut up into 1-inch segments. A LECO Carbon Analyzer is then used to measure the amount of deposition that has occurred inside the tube. This deposition is plotted and provides a quantitative measurement of relative additive performance. Again since a quantitative limit could not be established for acceptance criteria for the BFA, acceptance was based on the deposition for a candidate additive being not more than the deposition for the baseline fuel. Figure 11 shows the BFA disassembled and as assembled and installed in the ARSFSS rig.

4.3.1.5 ARSFSS Acceptance Criteria

In summary, acceptance criteria for the ARSFSS testing was as follows:

- **Servo Valve Hysteresis** – Lower than or equivalent to baseline fuel performance.
- **Servo Valve Deposition Appearance** - Less than (cleaner) or equivalent to baseline fuel performance.
- **FDV Hysteresis** – Lower than or equivalent to baseline fuel performance.
- **FDV Deposition Appearance (Valve components and Screen)** - Less than (cleaner) or equivalent to baseline fuel performance.
- **FCOC and BFA Deposition (Leco Carbon Analyzer)** - Better an or equivalent to baseline fuel performance.

4.4 Mission Cycles

In addition to the capability for the ARSFSS to provide a realistic environment for the fuels under test, it also possess a very unique ability to impose changing conditions in real time – thereby simulating the actual conditions a fuel system would see in actual flight scenarios. These scenarios are called missions. An ARSFSS mission is based, in as realistic a way as possible, on real-world missions. Early in the development of the ARSFSS, AFRL enlisted the aid of a major aircraft engine OEM to develop plausible and executable missions for the ARSFSS. At that time, an advanced aircraft/engine was being developed and the OEM had developed a mission cycle for other testing which they designated the Generic Durability Test Cycle (GDTC). This single mission type represented a composite of all the types of missions that the aircraft and engine would be expected to experience over its service lifetime. AFRL adapted this GDTC Mission for the ARSFSS and it became the standard mission scenario that has been used by the ARSFSS for almost three decades. Over that time, the original GDTC mission has been further tweaked and adapted based on ARSFSS rig operation experience. Today, the ARSFSS GDTC mission consists of 6 mission segments representing a generic aircraft mission. These 6 segments are, in order of execution, (1) Ground Idle 1, (2) High Power Cruise, (3) Low Power Cruise, (4) Combat, (5) Descent and (6) Ground Idle 2 (exactly the same as Ground Idle 1). Since advanced aircraft fuel systems recirculate fuel from some point on the engine or airframe back to the wing and/or body fuel tanks for thermal management purposes, the ARSFSS GDTC mission includes this provision as well. Flows are thus described as ‘core burn flow’ and ‘recirculation fuel flow’. Core burn flow is the flow that feeds the combustor nozzle and provides propulsion. Recirculation flow is flow that is used for thermal management purposes. In the case of the ARSFSS, this recirculation flow is taken off of the engine simulator just downstream of the FCOC and it is sent back to the body tank. The amount of core and recirculation flows is dependent upon the mission segment and is part of the GDTC mission profile. Figure 12 shows a plot of core and recirculation flows for the GDTC mission.

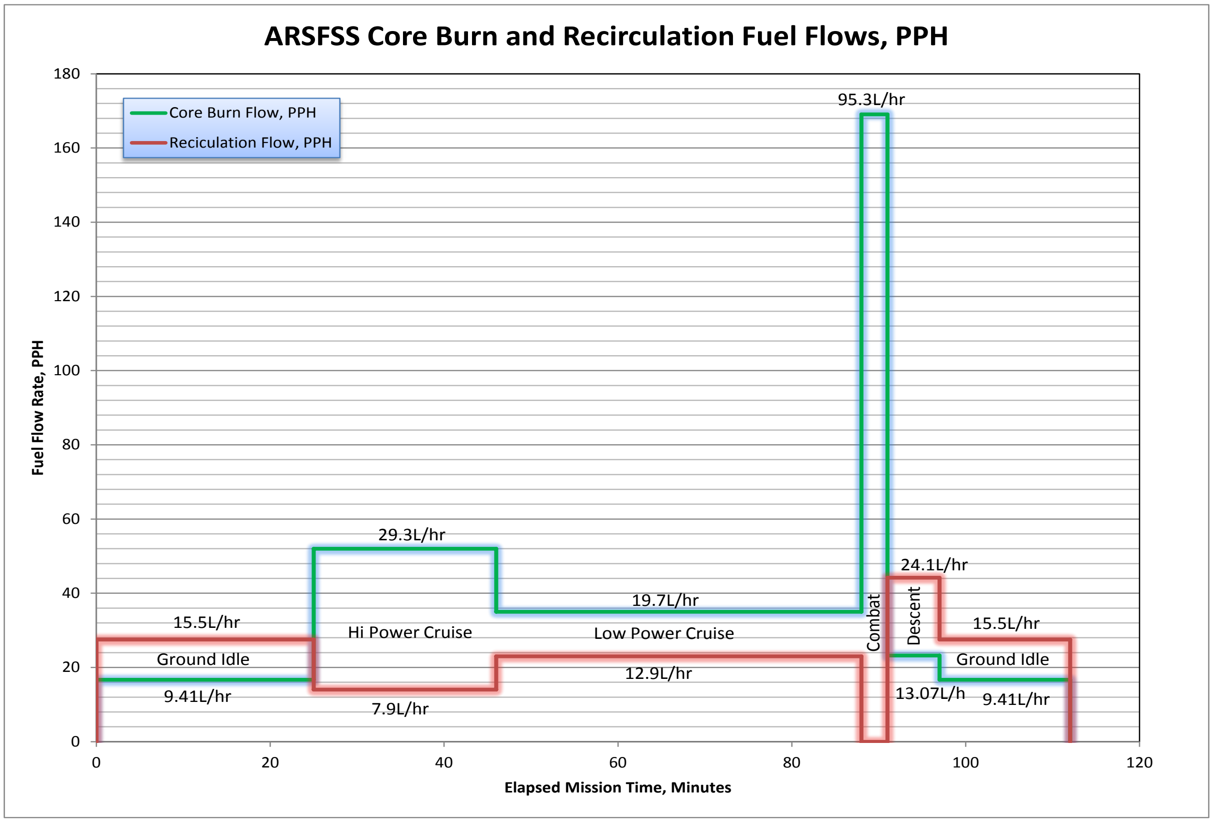


Figure 12 – Plot Core and Recirculation Fuel Flows As A Function of Elapsed Mission Time

In addition to fuel flows, each segment of the GDTC mission imposes wetted wall and bulk fuel temperatures based on real-world aircraft experience. These conditions are imposed at or upon critical aircraft components or fuel flow critical points. Table 3 shows the conditions imposed at various critical test points for the GDTC mission with a target wetted-wall temperature in the BFA of 450 °F (232 °C). Mission control points in Table 3 refer to points in the Figure 3 flow schematic represented by crimson stars. The outlet temperature of the Airframe Heat Exchanger (AFHX) represents a maximum temperature of fuel at the airframe/engine interface. This represents all the heat loads of the airframe (boost and transfer pumps, environmental controls, hydraulics, electronics, etc.) and includes the heat from fuel recirculation. For various reasons, most aircraft limit this temperature to a maximum of 285 °F (140 °C) due to materials and electronics limitations. In the flow schematic, fuel entering the engine is fed to the HP engine pump. In a normal aircraft system, this pump runs continuously and fuel is throttled by controls resulting in the pump working the fuel which causes bulk fuel temperature to increase.

In the case of the ARSFSS, the pump used for simulation is incapable of generating the required heat to fully simulate a conventional HP pump so a tube-and-shell heat exchanger is positioned downstream of the ARSFSS HP pump. Fuel leaving this combination of HP pump and heat exchanger represents the bulk fuel inlet temperature to the inlet of the FCOC of approximately the right magnitude. In the engine FCOC, the maximum outlet fuel temperature is limited to 325 °F (163 °C). This is based upon the design of the engine oil lubrication system which limits the maximum oil temperature to this value. Fuel departing the FCOC first passes through the FDV which is housed in an assembly for the valve. This device is not actively heated so any deposition in this area is a result of deposition in the bulk fuel.

Fuel exiting the FDV passes through the BFA which is actively heated by electrical induction. The target temperature for the BFA is a wetted-wall temperature (WWT) and is based upon the temperature in the 8th segment of the BFA at the inner wall where fuel is in contact with the inner surface of the tube. In the GDTC mission, this temperature is limited to a maximum of 450 °F (232 °C). It should be noted from

Table 3 that no target temperature conditions are imposed by the GDTC mission for the Combat mission element. This is because all fuel flow is dedicated to propulsion and no fuel is being recirculated. Fuel temperatures are permitted to be whatever the system equilibrium dynamics dictate for this condition. This is representative of actual aircraft operations.

In previous test programs involving ARSFSS testing, especially programs seeking to develop thermal stability-improving additives, higher temperatures for FCOC Inlet, FCOC Outlet and BFA WWT are imposed. In this way, additives and fuels of higher thermal stability can be evaluated. For the purposes of such programs, three different versions of the basic GDTC mission have typically been used and have been designated as LT (low temperature-range), MT (moderate-temperature range) and HT (high temperature range). Roughly, these temperature ranges represent conditions that would be expected in three different types of aircraft fuel systems with LT conditions loosely representing legacy military and commercial aircraft conditions, MT loosely representing more current military and commercial aircraft conditions and HT loosely representing much more advanced military aircraft conditions. Table 4 shows the modified GDTC mission parameters for these alternate temperature ranges.

While the ARSFSS attempts to operate at conditions representative of real-world aircraft, this does not necessarily mean that one hour of ARSFSS operation is equivalent to one hour of aircraft operation since the GDTC protocol is based on a composite experience over an aircraft's typical lifetime. As such, the GDTC protocol represents a somewhat accelerated test – but not to the point where time-for-temperature trade-off compromises test integrity by altering fuel deposition chemistries significantly outside the normal experience of an aircraft.

4.5 Rig and Test Article Preparation

Unless a prior program has used a fuel, additive or contaminant that is somewhat 'exotic' and could likely contaminate the ARSFSS for future testing, only fuel flushing is performed as part of rig preparation. This is typically accomplished as a part of the hysteresis baseline determinations for the SV and the FDV.

The BFA and FCOC tubes (316SS) are cut from a stock supply of tubing. Typically enough tubing is acquired so that the same tubing material is used throughout at test series. These tubes, once cut to size,

Table 3 - Mission Parameters for Generic Durability Test Cycle Mission with a Target BFA Wetted-Wall Temperature (WWT) of 450 °F (232 °C)

Mission Parameter	Mission Control Point	Mission Segment Number and Name					
		Ground Idle 1	Hi Pwr Cruise	Lw Pwr Cruise	Combat	Descent	Ground Idle 2
		1	2	3	4	5	6
Start Time, El. Min	N/A	0	25	46	88	91	97
End Time, El. Min	N/A	25	46	88	91	97	112
Duration, Min	N/A	25	21	42	3	6	15
Burn Flow, PPH	4	16.7	52	35	169.1	23.2	16.7
Recirc Flow, PPH	3	27.5	14	23	0	44.2	27.5
FCOC Fuel In, °F	2	300	300	300	NC	300	300
FCOC Fuel Out, °F	3	325	325	325	NC	325	325
AFHX Fuel Out, °F	1	285	285	285	NC	285	285
BFA Max WWT, °F	4	450	450	450	NC	450	450

NC = Not Controlled   NA = Not Applicable are cleaned at ambient temperature with a solution of Blue Gold Industrial Cleaner (Carroll Company, 2900 West Kingsley Road, Garland TX 75041, website http://www.bluegoldcleaner.com/cleaner.aspx; Phone (501)988-1311) and water (1 part cleaner to 5 parts RO water) in an ultrasonic cleaner for 8 hours and then rinsed with fresh RO water, air-dried at ambient temperature and stored. All SV and FDV components are cleaned the same way. After cleaning, SV and FDV components are stored submerged in clean fresh (non-FAME) fuel (JP-8 or Jet A) to prevent corrosion and to ‘age’ the components prior to assembly and preparation.

Table 4 – Mission Parameters for the HT, MT and LT Temperature Profiles, GDTC Mission

Mission Parameter	Control Point	Mission Segment Number and Name																	
		Ground Idle 1			Hi Pwr Cruise			Low Pwr Cruise			Combat			Descent			Ground Idle 2		
		1			2			3			4			5			6		
Temperature Profile		HT	MT	LT	HT	MT	LT	HT	MT	LT	HT	MT	LT	HT	MT	LT	HT	MT	LT
Start Time, Elapsed Minutes		0	0	0	25	25	25	46	46	46	88	88	88	91	91	91	97	97	97
End Time, Elapsed Minutes		25	25	25	46	46	46	88	88	88	91	91	91	97	97	97	112	112	112
Duration, Minutes		25	25	25	21	21	21	42	42	42	3	3	3	6	6	6	15	15	15
Burn Flow, PPH		16.7	16.7	16.7	52	52	52	35	35	35	169.1	169.1	169.1	23.2	23.2	23.2	16.7	16.7	16.7
Recirulation Flow, PPH		27.5	27.5	27.5	14	14	14	23	23	23	0	0	0	44.2	44.2	44.2	27.5	27.5	27.5
Total Flow, PPH		44.2	44.2	44.2	66	66	66	58	58	58	169.1	169.1	169.1	67.4	67.4	67.4	44.2	44.2	44.2
Airframe HX Bulk Fuel Out, °F (°C)	1	285(140)	285(140)	285(140)	285(140)	285(140)	285(140)	285(140)	285(140)	285(140)	NC	NC	NC	285(140)	285(140)	285(140)	285(140)	285(140)	285(140)
FCOC Inlet Temp, °F (°C)	2	325(163)	325(163)	300(149)	325(163)	325(163)	300(149)	325(163)	325(163)	300(149)	NC	NC	NC	350(177)	325(163)	300(149)	350(177)	325(163)	300(149)
FCOC Outlet Temp, °F (°C)	3	375(191)	350(177)	325(163)	375(191)	350(177)	325(163)	375(191)	350(177)	325(163)	NC	NC	NC	375(191)	350(177)	325(163)	375(191)	350(177)	325(163)
BFA Max Wetted Wall Temp, °F (°C)	4	500(260)	475(246)	450(232)	500(260)	475(246)	450(232)	500(260)	475(246)	450(232)	NC	NC	NC	500(260)	475(246)	450(232)	500(260)	475(246)	450(232)
NC = Not Controlled; HT = High Temp; MT = Moderate Temp; LT = Low Temp																			

Note: Due to the high fuel flow rates of the Combat mission segment, the temperatures are allowed to 'free float' to whatever value they want to go to during these high flows. This is similar to the behavior of a real world engine. While this high flow, low temperature condition does not have any significant impact on the thermal stability or thermal management of the system, it serves mainly to emulate a condition where high fuel flow rates could possibly dislodge fuel deposits and force them downstream and perhaps out of the system. This is in keeping with what would be expected in a real-world system.

4.6 Overall Test Plan and Deviations

4.6.1 Initial Test Plan

An initial test plan was prepared and developed jointly amongst the EI-JIP team and is shown in Table 5. This plan was developed based on

a) Evaluating baseline Jet A/Jet A+400 ppm FAME fuels under LT, MT and HT conditions
b) Selecting the condition most sensitive to the presence of FAME
c) Evaluating the use of additives and reduced FAME concentrations to mitigate an deposit-forming tendencies detected

However, on commencement of the program, some variation in ARSFSS results was noted and a revised test plan had to be developed. This new plan was jointly developed with the Industry Members and adopted as the final go-forward plan (Table 6).

4.6.2 Revised Test Plan and Deviations

The revised plan, Table 6, remained essentially unchanged from the start of the program to the end with the exception Run 95 which was a repeat of Run 92 – which was necessary due to a malfunction in the BFA induction heater which resulted in the system being unable to maintain BFA wetted-wall temperature through the duration of the run. Another exception was the inclusion of a Long Duration Switched Fuel Protocol (LDSF) run and several Extended Duration Thermal Stability Test (EDTST) Protocol runs. The nature of these protocols is discussed in the following section. These protocols were conceived and used in operation with the intent of trying to sort out some of the data uncertainties that were observed in the program. As such, **Table 6 shows the ARFSS Run numbers and Run conditions as they were executed, but not necessarily in the order executed**.

Table 5 – Original Test Plan

FAME CONTAMINATION PRIMARY TEST PLAN															
Run No.	**Test Description/Goal**	**Missions[1]**	**Fuel Type [2]**	**Fuel Qty (gal)**	**FAME PPM**	**FCOC Bulk Inlet °F**	**BFA Bulk Inlet °F**	**BFA Max WWT °F**	**Pretest Flush**	**Overnight Soak**	**Cleaning Procedure**	**CI/LI mg/L**	**MDA mg/L**	**+100 ppmv**	**Notes**
Preliminary Program with FAME Insensitive Fuel															
PHASE 0 (A) - Establish Basic Operational Parameters/Effect															
90	Baseline Jet A-1	65 (see note 1)	Jet A-1 (POSF4877) (Note 3)	900	0	325	350	475	Jet A-1 (FI)	Jet A-1 (FI)	AFRL	0	0	0	Test FAME insensitive fuel at Intermediate aircraft temperature profile - initial evaluation prior to main study.
91	Jet A-1 + 400 ppm FAME	65	Jet A-1 (POSF4877) (Note 3)	900	400	325	350	475	Jet A-1 (FI)+ FAME	Jet A-1 (FI) + FAME	AFRL	0	0	0	Test FAME contaminated insensitive fuel at Intermediate aircraft temperature profile - initial evaluation prior to main study.
Review	***Review data and assess impact of running FAME insensitive base fuel / 400 ppm contaminated fuel on rig operating conditions and rate of deposit formation.***														
Main Program with FAME Sensitive Fuel															
PHASE I (A) - Establish Basic Operational Parameters/Effect															
92	Baseline Jet A	65 (see note 1)	Jet A (FS)	900	0	350	375	500	Jet A	Jet A	AFRL	0	0	0	Testing at three temperature profiles representative of Legacy, Intermediate, and Advanced aircraft (military and commercial) to make sure the most effective temperature profile has been selected.
93	Baseline Jet A	65	Jet A (FS)	900	0	325	350	475	Jet A	Jet A	AFRL	0	0	0	
94	Baseline Jet A	65	Jet A (FS)	900	0	300	325	450	Jet A	Jet A	AFRL	0	0	0	
95	Baseline Jet A	65 (see note 1)	Jet A (FS)	900	0	350	375	500	Jet A	Jet A	AFRL	0	0	0	Re-run of Run 92 due to malfuntion in achieving heater steady state power output during the Run.
96	Jet A + 400 ppm FAME	65	Jet A (FS)	900	400	350	375	500	Jet A + FAME	Jet A + FAME	AFRL	0	0	0	Testing at three temperature profiles using FAME-contaminated fuel. System flush and overnight soak in FAME-contaminated fuel. This directly relates to the above baseline tests and will allow evaluation of potential FAME impact to Legacy, Intermediate and Advanced aircraft configurations (military and commercial). It will also allow for final selection of test conditions for additional testing as required.
Review	***Stage Gate: If burner feed-arm input energy is significantly different for 400 ppm FAME undertake Run 99 using same thermal conditions followed by Industry review.***														
97	Jet A + 400 ppm FAME	65	Jet A (FS)	900	400	325	350	475	Jet A + FAME	Jet A + FAME	AFRL	0	0	0	
98	Jet A + 400 ppm FAME	65	Jet A (FS)	900	400	300	325	450	Jet A + FAME	Jet A + FAME	AFRL	0	0	0	
Review	***Review data and assess impact of FAME. If 400 ppm FAME gives no significant deposition impact, review fuel/rigs and seek technical explanation. Consider 100 ppm FAME approval based on the data. If significant deposition is apparent from FAME contamination, select a test***														
PHASE I (B) - Initial Evaluation of FAME Impact Without Overnight Soaking and Use of Additives to Control Deposition															
99	Baseline Jet A	65	Jet A (FS)	900	0	Phase I (A) Profile (TBD)			Jet A	Jet A	AFRL	0	0	0	Re-baseline at optimum conditions as determined by evaluation of data from Phase I, AFRL cleaning procedure
100	Jet A + 400 ppm FAME No FAME Soak or Flush	65	Jet A (FS)	900	400	Phase I (A) Profile (TBD)			Jet A	Jet A	AFRL	0	0	0	Optimum test conditions with FAME but **no FAME flush and No FAME overnight soak**; AFRL cleaning procedure
101	Jet A + 400 ppm FAME	65	Jet A (FS)	900	400	Phase I (A) Profile (TBD)			TBD			23	0	0	Optimum test conditions and preparatory procedures with 400 ppm FAME - test CI/LI option. If successful, long-term test in PHASE II
102	Jet A + 400 ppm FAME	65	Jet A (FS)	900	400	Phase I (A) Profile (TBD)			TBD			0	2	0	Optimum test conditions and preparatory procedures with 400 ppm FAME - test MDA option. If successful, long-term test in PHASE II.
Review	***Completion of scoping investigation to determine if 400ppm FAME gives deposits in line with JIP work / if additive remediation options viable.***														
PHASE II (A) - Specific Evaluation of AFTSTU Cleaning Procedure with/without FAME Flush and Overnight Soaking															
103	Baseline Jet A AFTSTU Prep	65	Jet A (FS)	900	0	Phase I (A) Profile (TBD)			Jet A	Jet A	AFTSTU	0	0	0	Re-baseline at optimum conditions as determined by evaluation of data from Phase I, AFTSTU cleaning procedure
104	Jet A + 400 ppm FAME With FAME Flush and Soak; AFTSTU Prep	65	Jet A (FS)	900	400	Phase I (A) Profile (TBD)			Jet A + FAME	Jet A + FAME	AFTSTU	0	0	0	Optimum test conditions with FAME but with **FAME flush and FAME overnight soak**; AFTSTU cleaning procedure
105	Jet A + 400 ppm FAME No FAME Soak or Flush; AFTSTU Prep	65	Jet A (FS)	900	400	Phase I (A) Profile (TBD)			Jet A	Jet A	AFTSTU	0	0	0	Optimum test conditions with FAME but **no FAME flush and No FAME overnight soak**; AFTSTU cleaning procedure
Review	***Collect and analyse data. If system soak or cleaning procedures impacts deposition with FAME, OEMs to consider relevance. If no impact from cleaning or soak is apparent, standardize on one temperature profile and one preparatory/cleaning procedure for all remaining testing.***														
PHASE II (B) - Determine "No-Harm" Limit If FAME Gives Significant Deleterious Deposition @ 400 ppm															
106	Baseline Jet A	65	Jet A (FS)	900	0	Phase I (A) Profile (TBD)			TBD			0	0	0	Baseline at Optimum test conditions and preparatory procedures
107	Jet A + 200 ppm FAME	65	Jet A (FS)	900	200	Phase I (A) Profile (TBD)			TBD			0	0	0	Optimum test conditions and preparatory procedures with 200 ppm FAME
108	Jet A + 200 ppm FAME	65	Jet A (FS)	900	200	Phase I (A) Profile (TBD)			TBD			0	0	0	Optimum test conditions and preparatory procedures with 200 ppm FAME ; test repeat to assess repeatability and reliability
109	Baseline Jet A	65	Jet A (FS)	900	0	Phase I (A) Profile (TBD)			TBD			0	0	0	Re-baseline at Optimum test conditions and preparatory procedures to check for baseline shift and check repeatability after FAME use
Review	***Collect and analyse data. Prepare linear interpolation of data to estimate possible 'no-harm' limit for FAME if 400 ppm gives significant deleterious deposition. Proceed to Phase II(C) using this interpolated 'no-harm' limit.***														
PHASE II (C) - Determine Impact of Long Term FAME Contamination and Control Option															
110	Long Term Baseline	130	Jet A (FS)	1800	0	Phase I (A) Profile (TBD)			TBD			0	0	0	Baseline at Optimum test conditions and preparatory procedures. Determine deposition rate of baseline fuel for long-term operations (130 or more mission cycles). Compare to previous data at 65 missions.
111	Long Term FAME Remediation	130	Jet A (FS)	1800	400 ppm or "No-Harm"	Phase I (A) Profile (TBD)			TBD			TBD	TBD	TBD	FAME contamination at lower limit or 400ppm + additives dependent on Industry consensus. Optimum test conditions and preparatory procedures. Determine if low FAME concentration/additives manages issue over long-term operations (130 or more mission cycles). Compare to previous data at 65 missions.
Review	***Collect and analyse data. Consider additional testing if required.***														

Notes:

1. Typically, 65 missions will be used based on the Generic Durability Test Cycle mission profile normally used for the ARSFSS. However, the number of missions may be increased as needed.

2. Jet A1 (FI) and Jet A (FS) represent FAME insensitive and FAME sensitive fuels respectively as determine by the ExxonMobil extended JFTOT(TM) test.

3. POSF-4877 is assumed to be FAME-insensitive as determined by ExxonMobil slow JFTOT test

Table 6 – Revised Test Plan and Mission Conditions

FAME CONTAMINATION TEST PLAN AS EXECUTED													
Run No.	Test Date (Start)	Test Description	Mission Type	Missions[1] or Hours	Fuel Type [2]	FAME PPM	FCOC Bulk Inlet °F [3]	FCOC Bulk Fuel Outlet °F	BFA Max WWT °F	Pretest Flush	Overnight Soak	Cleaning Procedure	Run Note
90	25-Mar-13	Baseline Jet A	EDTST	72 Hrs	Jet A	0	325	375	510	Jet A	Jet A	AFRL	*F*
91	2-Apr-13	Jet A + 400 ppm FAME	EDTST	72 Hrs	Jet A	400	325	375	510	Jet A + FAME	Jet A + FAME	AFRL	*F*
92	26-Sep-12	Baseline Jet A	HT	65	Jet A	0	325	375	500	Jet A	Jet A	AFRL	*A*
93	3-Oct-12	Baseline Jet A	MT	65	Jet A	0	325	350	475	Jet A	Jet A	AFRL	*A*
94	10-Oct-12	Baseline Jet A	LT	65	Jet A	0	300	325	450	Jet A	Jet A	AFRL	*A*
95	24-Oct-12	Baseline Jet A	HT	65	Jet A	0	325	375	500	Jet A	Jet A	AFRL	*B*
96	1-Nov-12	Jet A + 400 ppm FAME	HT	65	Jet A	400	325	375	500	Jet A + FAME	Jet A + FAME	AFRL	*C*
97	29-Nov-12	Jet A + 400 ppm FAME	MT	65	Jet A	400	325	350	475	Jet A + FAME	Jet A + FAME	AFRL	*C*
98	15-Nov-12	Jet A + 400 ppm FAME	LT	65	Jet A	400	300	325	450	Jet A + FAME	Jet A + FAME	AFRL	*C*
99	10-Jan-13	Jet A + 400 ppm FAME	HT	65	Jet A	400	325	375	500	Jet A + FAME	Jet A + FAME	AFRL	
100	17-Jan-13	Jet A + 400 ppm FAME	LT	45	Jet A	400	300	325	450	Jet A + FAME	Jet A + FAME	AFRL	*D*
101	24-Jan-13	Jet A + 400 ppm FAME	LT	65	Jet A	400	300	325	450	Jet A + FAME	Jet A + FAME	AFRL	
102	31-Jan-13	Jet A + 400 ppm FAME	HT	65	Jet A	400	325	375	500	Jet A + FAME	Jet A + FAME	AFRL	
103	13-Feb-13	Baseline Jet A	HT	65	Jet A	0	325	375	500	Jet A	Jet A	AFRL	
104	21-Feb-13	Jet A + 400 ppm FAME	HT	65	Jet A	400	325	375	500	Jet A + FAME	Jet A + FAME	AFRL	
105	28-Feb-13	Switched Fuel	HT	210	Jet A	400	325	375	510	Jet A + FAME	Jet A + FAME	AFRL	*E*
106	29-Apr-13	Jet A + 400 ppm FAME	EDTST	72 Hrs	Jet A	400	325	375	510	Jet A + FAME	Jet A + FAME	AFRL	*F*
107	6-May-13	Baseline Jet A	EDTST	72 Hrs	Jet A	0	325	375	510	Jet A	Jet A	AFRL	*F*

NOTE 1:	Typically, 65 missions will be used based on the Generic Durability Test Cycle mission profile normally used for the ARSFSS. However, the number of missions may be increased as needed.
NOTE 2:	*FAME sensitive fuel as determine by the ExxonMobil extended JFTOT(TM) test.*
NOTE 3:	*FCOC Bulk Fuel Inlet Temp not to exceed 325°F due to aircraft design limits*
NOTE A:	Testing at three temperature profiles representative of Legacy, Intermediate, and Advanced aircraft (military and commercial) to make sure the most effective temperature profile has been selected.
NOTE B:	Re-run of Run 92 due to malfuntion in achieving heater steady state power output during the Run.
NOTE C:	Testing at three temperature profiles using FAME-contaminated fuel. System flush and overnight soak in FAME-contaminated fuel. This directly relates to the above baseline tests and will allow evaluation of potential FAME impact to Legacy, Intermediate and Advanced aircraft configurations (military and commercial). It will also allow for final selection of test conditions for additional testing as required.
NOTE D:	Depositioni caused BFA WWT to excede system safety limits. Test terminated at 45 missions.
NOTE E:	Switched Fuel Testing Protocol - Combined FAME/Baseline run to determine behavior when transitioning from FAME to Baseline fuel. Test run until BFA temperature increase documented and then switch to Jet A Baseline to see if trend continues, stabilizes or reduces. This should indicate a true effect of FAME if any. Most of test run at 510 °F WWT BFA. Total Run 212 Hrs, 110 mission cycles.
NOTE F:	EDTST-Mode testing accomplished AFTER the rest of the testing was done. Despite the run numbers (90 and 91), these tests were performed AT THE END of this work.

4.7 Modified Testing Protocols Implemented

Initially, all testing was to be performed using the Generic Durability Test Cycle (GDTC) protocol. This protocol has been the primary method used for ARSFSS testing over nearly the last three decades. However, as testing proceeded in this program, it was observed that data was a little more scattered than expected. It was as if the ARSFSS was being operated in a temperature regime where the fuel's inherent thermal stability nature was on a knife's edge with regard to its response to elevated temperatures. There was concern that this behavior might lead to questions regarding testing validity so two new testing protocols were developed to help sort out the reasons for the variations and to provide testing protocols that might be less susceptible to such variation. The following sub-sections describe each of the additional testing protocols developed and used during this program.

4.7.1 Long Duration Switched Fuel Protocol (LDSF)

ARSFSS testing using the Generic Durability Test Cycle mission set is normally the way the ARSFSS is operated. However, since each individual run (a mission set of 65+ missions) involves the replacement of test hardware components, some data repeatability issues may arise. This is particularly a problem when there are limited quantities of fuel and when fuel thermal stability behavior is 'erratic'.

As deposition forms in the BFA, this deposition lowers the heat transfer rate to the bulk fuel from the BFA sidewall. This results in a temperature rise in the BFA sidewall for fixed heater outputs. In this manner, BFA wetted wall temperature (WWT) rise is a direct indication of deposition occurring along the wall within the BFA.

During this program, the fuel's thermal stability performance under high temperature conditions, as manifested in BFA WWT changes and carbon deposition, exhibited some anomalous behaviors. In an attempt to understand these behaviors, a new ARSFSS testing protocol was conceived which would look strictly at BFA and FCOC wetted-wall temperature changes with the only changes to the system during the test being the change in fuel. This protocol involves a long duration run where baseline and test fuel is alternated periodically and the temperature rise in the Burner Feed Arm (BFA) is monitored. In this operations scenario, the variability of changing hardware components (BFA tubes, FCOC tubes, Servo and Flow Divider valves, etc.) is eliminated allowing of the variances in deposition to be more completely attributable to fuel differences. The down side to this style of testing is that flow valve hysteresis and carbon deposition (in terms of µgrams/cm²) are no longer available as a part of the data set.

A more detailed discussion of this protocol is reserved for Appendix B, but fundamentally, the concept is that if the only change was the fuel, if there were indeed an impact on fuel thermal stability, it should manifest itself in how the BFA WWT change-rate increases over the duration of the run. Because this protocol involves at least two fuel switches, it was certain that this run would be of long duration. This would have the added benefit of demonstrating the long impact of operating with the additive beyond just 65 missions. it was hoped that this LDSF protocol would give a clearer indication of the impact of fuel thermal stability changes due to FAME contamination alone.

4.7.2 Extended Duration Thermal Stability Test Protocol (EDTST)

In the 1990s through about 2008, most of the thermal stability research performed at WPAFB was accomplished using one of three systems - two small bench-scale systems and one larger rig-scale system. The larger system was a steady-state test flowing fuel at a rate of 1 gallon per hour. The system was configured with a preheater and a heated test section. The test was operated 24/7 for about 96 hours and consumed about two drums of fuel. This larger rig, called the Extended Duration Thermal Stability Test (EDTST) logged over 50,000 test hours over the course of over two decades and was the backbone of most of the Air Force thermal stability research at rig scale. This rig saw a significant portion of its service in performing testing on the JP-8+100 candidate additives in the 1990s and 2000's. Typically for additive approval, many small bench-scale tests were performed to screen additives. Additives passing these small bench-scale tests were then evaluated in the EDTST. Many times additives that passed testing in the smaller scale tests did not pass in the EDTST. Those additives that did pass the EDTST were further evaluated using the ARSFSS. The progression from small scale bench to large scale rig tests allowed the additive or fuel to be evaluated in increasingly more realistic tests which assured that a fuel or additive that had passed through this gauntlet of testing would perform as expected in the real world.

In the 2008, the EDTST was removed from service after the completion of a program that evaluated Next Generation JP-8+100 additives. With other research requirements bidding for test cell space that the EDTST occupied, the EDTST was disassembled. Since that time, there have been times when having access to that original EDTST rig would have been desirable because of the rig's ability to balance realistic testing against minimal fuel requirements. In the current program, after observing some of the data, it was again desired to have access to a realistic fuel thermal stability test that would not consume hundreds of gallons of fuel for one test. Resurrecting the EDTST was considered but was not a viable option for several reasons. So the question became "Can the ARSFSS be operated in such a manner as to emulate the configuration and flow/temperature profile of the historic EDTST and perhaps accomplish the same thing?" The configuration of the ARSFSS with its capability to be operated in a variety of configurations with minimal system changes was assessed and it was determined that it would indeed be possible to develop a protocol for the ARSFSS that would emulate the configuration and fuel usage of the previous EDTST. This protocol was referred to as the EDTST protocol. In this protocol, the ARSFSS is fed from a single drum plumbed temporarily and directly into the rig (thereby eliminating the need to operate from a S-Farm fuel tank) and operated at fixed steady-state conditions for 72 hours of runtime. To be consistent with prior EDTST rig conditions, a fuel flow rate of 1 gallon per hour was desired. However, a review of the ARSFSS controls hardware and a short flow experiment determined that this low rate was not achievable for the ARSFSS without some modification. Therefore, a fixed Core burn flow rate of 13.1 PPH was established for the ARSFSS/EDTST configuration. A recirculation rate of 13.1 PPH was also established and these flow rates remained fixed for the duration of the 72-hour run. Bulk fuel temperature to the inlet of the FCOC was fixed at 325 °F (163 °C), FCOC fuel outlet temperature was fixed at 375 °F (191 °C) and the BFA wetted-wall temperature was fixed at 510 °F (266 °C).

The bulk of the test program had been completed by the time this EDTST protocol was conceived and developed. After the Run 105 test with the LDSF protocol, Runs 90, 91, 106 and 107 were performed using the new EDTST configuration and protocol. Later, two additional EDTST-mode runs were performed to provide additional data (Runs 108-109). Two more runs were added to evaluate FAME impact on a garden variety Jet A (Runs 110-111) as was conceived in the original test plan. The data from these runs are presented in the following section along with all of the other data obtained in the program.

5.0 Results and Data-Specific Discussions

All of the overall data results will be discussed in this section.

5.1 JFTOT® Breakpoint Deterioration

At various times throughout the program, JFTOT® (ASTM D3241) tests were performed on the baseline and additized fuels. Breakpoint determinations were also made. This allowed the tracking of the thermal stability 'health' of the fuel through the program. All JFTOT® and JFTOT® Breakpoint evaluations were performed by the Air Force Petroleum Agency (AFPA) local quality control lab located at Wright-Patterson AFB, Ohio to benefit precision/repeatability of tube rating.

Just two months after receipt of the FAME-sensitive fuel, the Breakpoint degraded by10 °C. Over the course of the program, the JFTOT® Breakpoint of the baseline fuel dropped 10 °C – outside of the normal repeatability which is typically 5 °C – and then returned to 280 °C at the end of the program. This deterioration in Breakpoint is within the experience of other researchers such as the University of Sheffield with regard to AFTSTU testing. This has posed problems for researchers regarding how to adequately account for this real or perceived degradation and the impact on the overall program data. However, there may be other explanations for this apparent restoration of JFTOT® Breakpoint that are beyond the scope of this report – such as a depletion of degradation reactants. On the other hand, the JFTOT® Breakpoint on the FAME-contaminated fuel seemed to deteriorate beyond the method repeatability leading to the assumption that at least for FAME-contaminated fuel, there was a real, not just perceived, deterioration in Breakpoint.

Figure 13 shows a summary of the Breakpoint temperatures for the fuel over the course of the program, starting in early September 2-12 through March 2013. It should also be noted that the bulk fuel

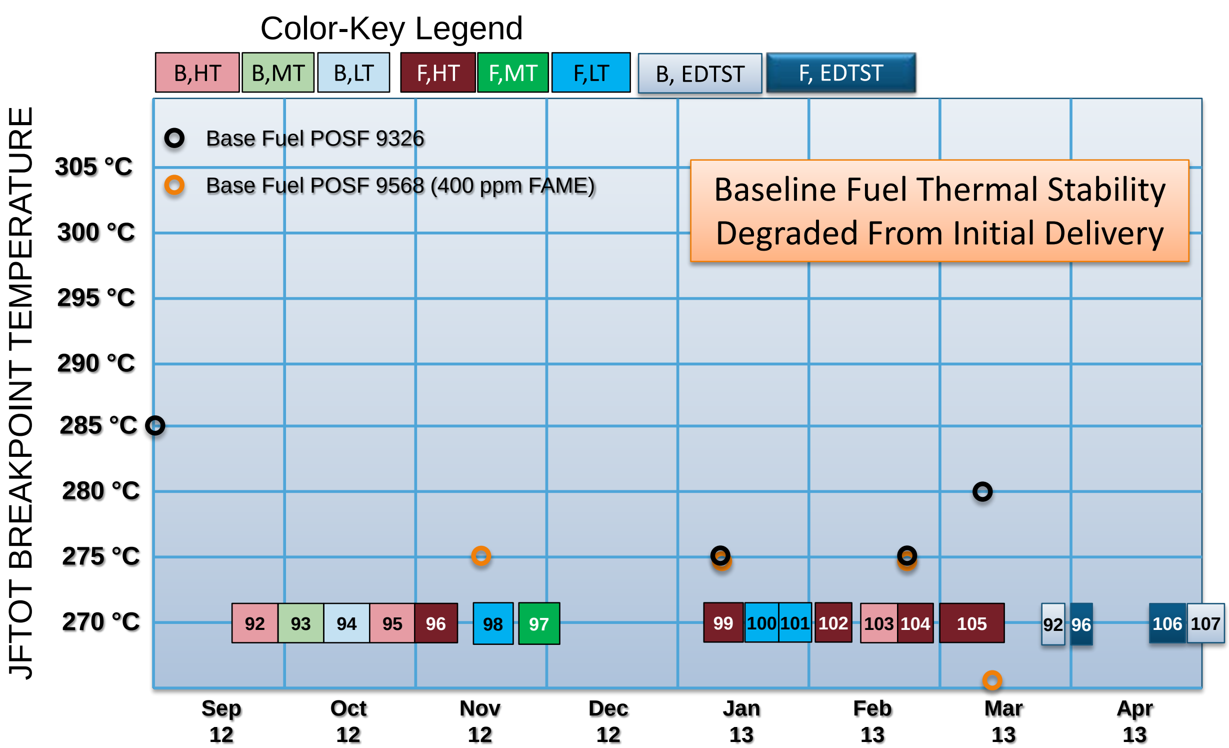


Figure 13 – JFTOT Breakpoint History

was stored, during the entire program, in an underground storage tank which experiences a relatively constant ground temperature of around 57 °F year round. It is also interesting to note that even though JFTOT® breakpoint deterioration occurred relatively early in the program, there was no discernible difference between the breakpoint of the baseline and additized fuel (even after the breakpoint deteriorated) until the end of the program where the breakpoint of the FAME contaminated fuel was lower than the baseline fuel. <u>This may indicate that FAME impact on thermal stability may only be a factor when fuel thermal stability is compromised to start with</u>.

Also shown on this figure is a timeline indicating which ARSFSS runs were performed in relationship to the Breakpoint determinations. It is interesting to note that the ARFSS runs that resulted in the highest deposition were runs that were accomplished after the breakpoint of the fuel had deteriorated.

It should be noted that since the ARSFSS represents a simulation of a real-world system, it cannot be directly inferred that a SLIGHT deterioration in JFTOT Breakpoint will manifest itself in a measureable, repeatable and commensurate experience in the ARSFSS. The ARSFSS is a simulation of many aspects of a very complex system where as the JFTOT and other similar bench-scale tests only look at one particular aspect of a complex system. It is therefore to be expected that a wider variance in results can be expected on such a complex system as the ARSFSS. ARSFSS results are more 'interpretive' than quantitative in many regards – especially with regard to the overall assessment of the composite test result.

5.2 Facility Fuel Filters

On the facility side of the ARSFSS, a single filter is in place to provide a final filtration step for incoming fuel from the fuel farm tanks. However, for this study, there was concern about the unknown behavior of the filter when exposed to FAME material. To avoid this issue, the filter was removed completely from the system. The S-Farm fuel tanks are in excellent condition and are extremely well maintained so the risk of debris or water coming from these tanks into the ARSFSS facility or rig was minimal. All ARSFSS runs were performed without this filter in place.

5.3 HP Pump Filters

In the HP Pump on the ARSFSS there is a filter on the inlet side of the pump (device number F301F1). This filter is a standard paper pleated filter (see Figure 14). The filter is a 10 micron rating with Micropleat® media (resin impregnated cellulose). The filter rated to 150 PSID and is a Purolator part number of 569408 (size 4). The specific filters used in the ARSFSS are procured as National Stock Number 4330-00-203-3593.

At the start of this program, the ARSFSS system was cleaned and flushed with the baseline Jet-A fuel (POSF9326) and all of the filters were replaced, including the HP Pump filter. The HP Pump Filter remained in place until after Run 102. Normally, this filter is not replaced after each test, only when

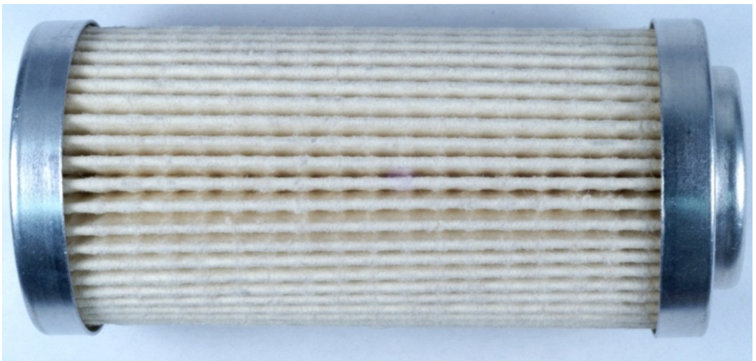


Figure 14 – New HP Pump Fuel Filter

beginning a new test series. However, after completing Run 102, the carbon deposition was so high that a decision was made to pull the filters and check them. Upon removing the HP Pump fuel filter, it was found to be severely contaminated with a dark material that resembled a carbon-type powder mixed with grease (see Figure 15).

Figure 15 – Sludge Deposit Removed From Filter Post Run 102

As the filter had not been changed since the beginning of the test program, the contamination on this filter was likely an accumulation of deposits from the whole test series. After Run 102, this filter was replaced before each Run, starting at Run 103. It is now standard procedure to replace this filter before each ARSFSS Run. The filter condition is also photographed at the end of each run and the pictures are part of the data set for each Run. Figure 16 shows a comparison between the post-run 102 filter and a new filter. Appendix G shows comparisons of the filters from Runs 103, 104, 90, 91, 106 and 107 and presents a discussion on the analyses of the sticky brown deposit found on the filters for FAME-contaminated fuel runs.

Figure 16 – Comparison of Post-Run 102 Filter and a New Filter

5.4 Dissolved Oxygen Measurements

Although not a requirement for this program, a dissolved oxygen sensor was installed on the ARSFSS to provide data about oxygen consumption during ARSFSS runs. Figure 2 shows the oxygen sensor and how it was installed on the ARSFSS. Although periodic measurements were made, no significant impact or reduction in dissolved oxygen was noted.

5.5 Overall Data Summary

Table 8 in Appendix C to this report shows an overall summary of the data from all of the Runs performed in this program. The following plots and discussion will delve into the details of these results.

5.6 Carbon Deposition – Burner Feed Arm (BFA)

5.6.1 Mission Cycle Testing

The bulk of the testing accomplished during this program on the ARSFSS was performed using the standard GDTC protocol. Figure 17 shows a composite plot of all the carbon deposition data for the program for all runs using the GDTC protocol. In this plot and subsequent plots, note the color scheme of the lines is significant.

- Red lines are for Runs using the High Temperature GDTC profile which is 325 °F (163 °C) FCOC Bulk Fuel Inlet Temperature, 375 °F (191 °C) FCOC Bulk Fuel Outlet Temperature, and 500 °F (260 °C) BFA Wetted- Wall Temperature (WWT)
- Green lines are for Runs using the Mid-Temperature GDTC profile which is 325 °F (163 °C) FCOC Bulk Fuel Inlet Temperature, 350 °F (177 °C) FCOC Bulk Fuel Outlet Temperature, and 475 °F (246 °C) BFA Wetted- Wall Temperature (WWT).
- Blue lines are for Runs using the Low Temperature GDTC profile which is 300 °F (149 °C) FCOC Bulk Fuel Inlet Temperature, 325 °F (163 °C) FCOC Bulk Fuel Outlet Temperature, and 450 °F (232 °C) BFA Wetted- Wall Temperature (WWT).

Solid lines indicate the run was with the baseline fuel and dotted lines indicate that the run was with baseline+400 ppm FAME fuel. **It should be noted that for the MT and HT conditions, FCOC Inlet bulk fuel temperature was 325 °F (163 °C). This is because, in actual hardware, fuel in this area of the fuel system is not permitted to be above 325 °F (163 °C) because of materials and system limitations.**

At the far left of the plot, two nearly vertical lines show results of Runs 99 and Run 102. These two runs exhibited extremely high deposition in the BFA. The WWT temperature rise in these runs, which is indicative of the amount of deposition going on inside the BFA, approached the safety limits of the ARSFSS control system. While Run 100 also exhibited very high deposition in the BFA, it was the only test that was actually terminated due to BFA WWT temperature rise exceeding the safety limits of the ARSFSS system. In this case the Run was terminated after 45 missions. Currently there is no explanation as to why Runs 99, 100 and 102 gave such high deposition levels since all other rig operating parameters remained within test tolerance.

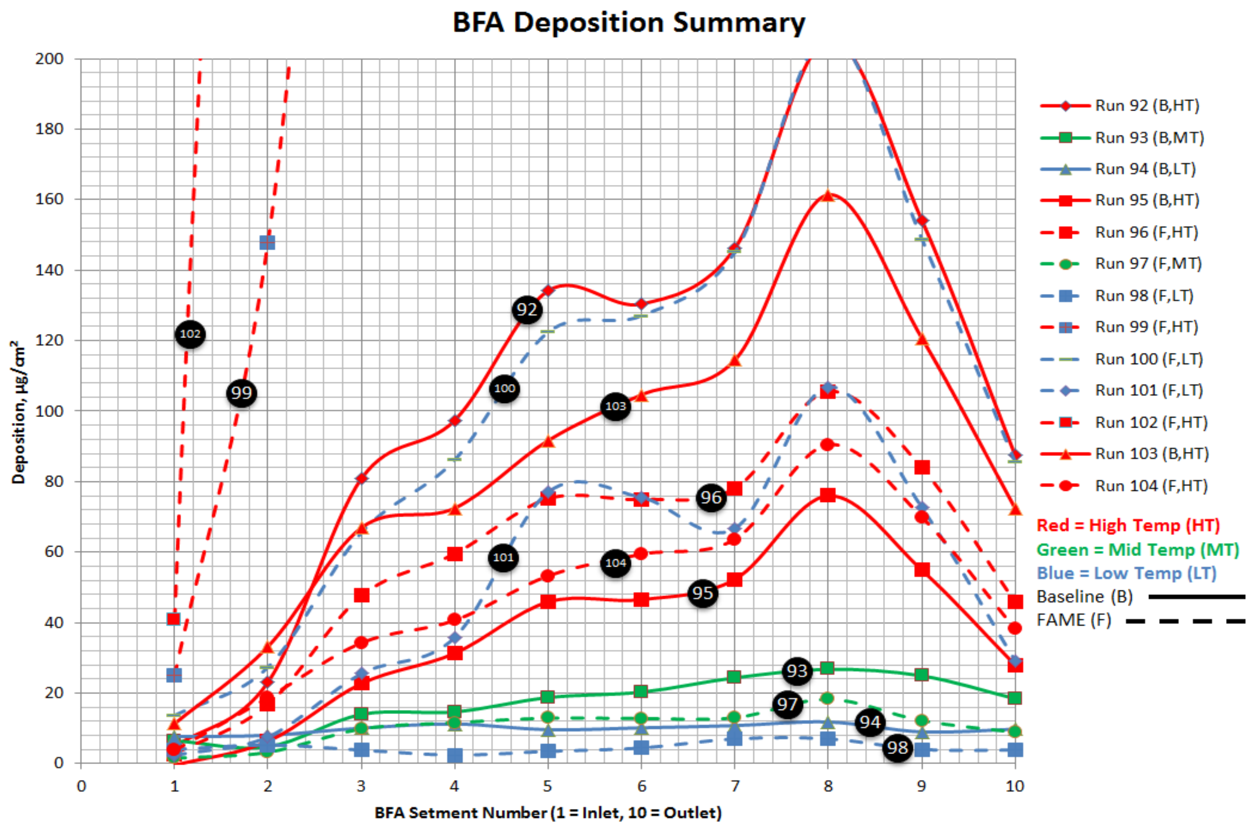


Figure 17 – Composite of All BFA Deposition Data

The early runs of Run 92 – Run 98 were performed <u>before</u> the thermal stability of the baseline fuel had deteriorated. These runs show a generally logical progression with regard to temperature regime of operation and BFA deposition. For example, looking at Figure 17 and looking primarily at the color grouping, it is clear that there is an impact of test temperature profile on the deposition in the BFA. Baseline Runs 92, 93, 94 and 95 exhibit a logical and expected progression of higher deposition at higher temperatures, lower deposition at lower temperatures. Run 95 was, in fact, a duplicate run of Run 92 and was performed because during Run 92, a problem with the BFA induction heater was encountered which did not allow the system to maintain a fixed input heat to the BFA. This situation was repaired between Runs 92 and 93. Run 95 was then repeated at the appropriate time to recapture the baseline data at that temperature condition.

When looking **WITHIN** the color groupings, for those Runs performed prior to the baseline fuel thermal stability degradation, there is no substantial discernible difference between baseline and contaminated fuel runs for the LT and MT conditions. The level of 'difference' observed for these test conditions, is certainly well within the 'scatter' of data that is normally observed. However, for the HT condition, we begin to see a little more significant increase in BFA deposition between the HT Baseline and the HT FAME Contamination runs (95 and 96). Figure 18 is a plot showing a subset of the data in Figure 17 – Runs 92-98 which were performed BEFORE the thermal stability of the baseline fuel degraded. So, it would appear that the greater discernibility is at the higher temperature conditions (assuming we drop out Run 92 as an outlier data point).

However, things begin to change starting with Run 99 (see Figure 19). This Run is the first after the degradation in baseline fuel thermal stability. Figure 13 shows that the thermal stability of FAME-contaminated fuel had deteriorated by November 2012. Lacking specific data, it is possible that the baseline fuel thermal stability has also degraded by this time. None the less, Run 99 was the first run after a shutdown of approximately a month. This break in the test program was necessary not only for the Holiday period, but also to accommodate scheduled repairs to other units in the facility. Post Run 99 we

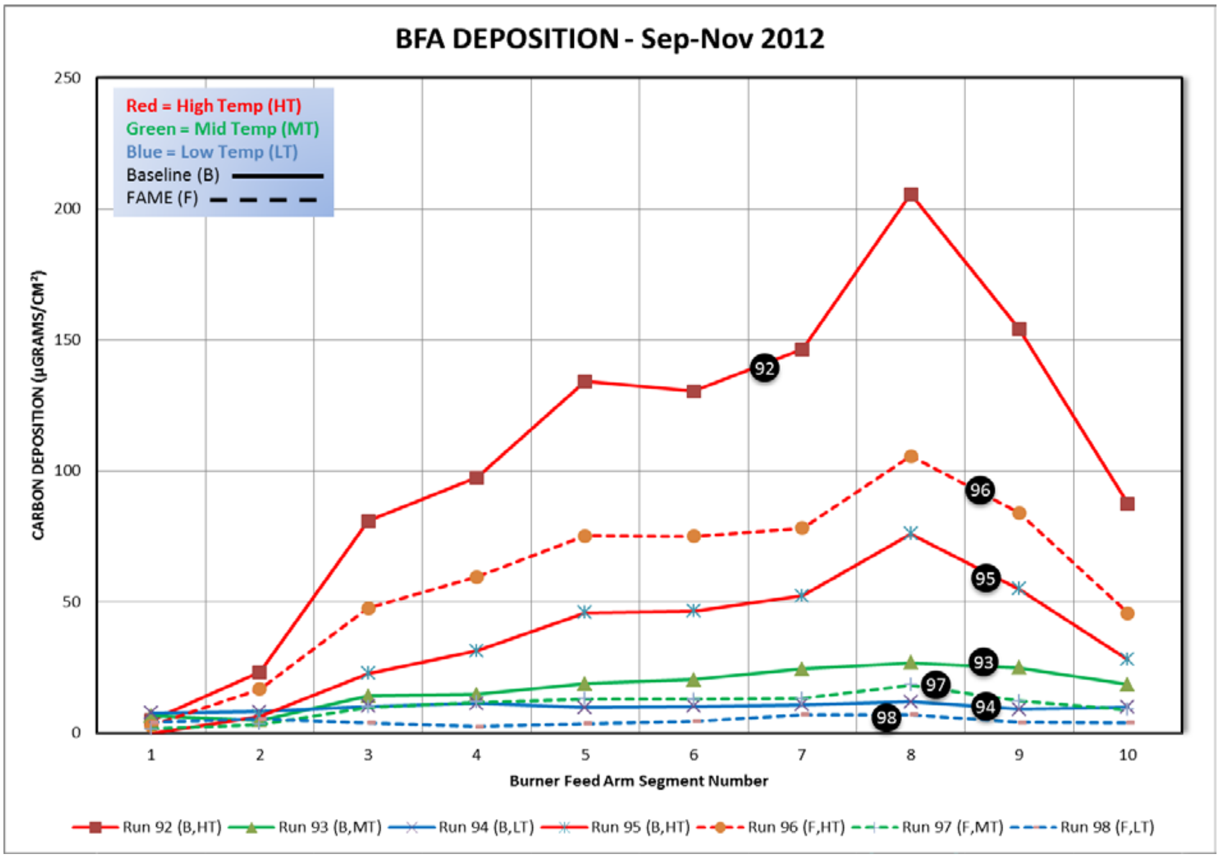


Figure 18 – BFA Deposition at All Temperatures For Baseline and Contaminated Fuel PRIOR to Baseline Fuel Breakpoint Degradation

begin to observe a distinct shift in deposition for both baseline and FAME-contaminated fuel. We no longer observe the logical and expected ranking of the BFA deposition according to test temperature. Data scatter is more pronounced in that we now have deposition data for FAME-contaminated runs at the MT condition that approaches or exceeds that of the baseline fuel at the HT condition. At the same time we have deposition for a FAME-contaminated fuel run at the HT condition that is virtually the same as deposition for that fuel at the MT condition. It would appear that the fuel property or properties that made this fuel FAME-sensitive may have given a fuel with a unique behavior upon degradation of the breakpoint temperature.

In an attempt to average out the scatter, a plot was prepared comparing the deposition of baseline and contaminated fuels across all temperature ranges for different time periods (Figure 20). In this plot, the deposition is more logical, with higher deposition experienced as thermal stability degradation occurred. From this plot, we can infer that there is little or no discernible difference in deposition between baseline and contaminated fuels. The greater impact upon deposition may be due to degradation in breakpoint rather than FAME contamination although this study lacks specific data to affirm this assumption.

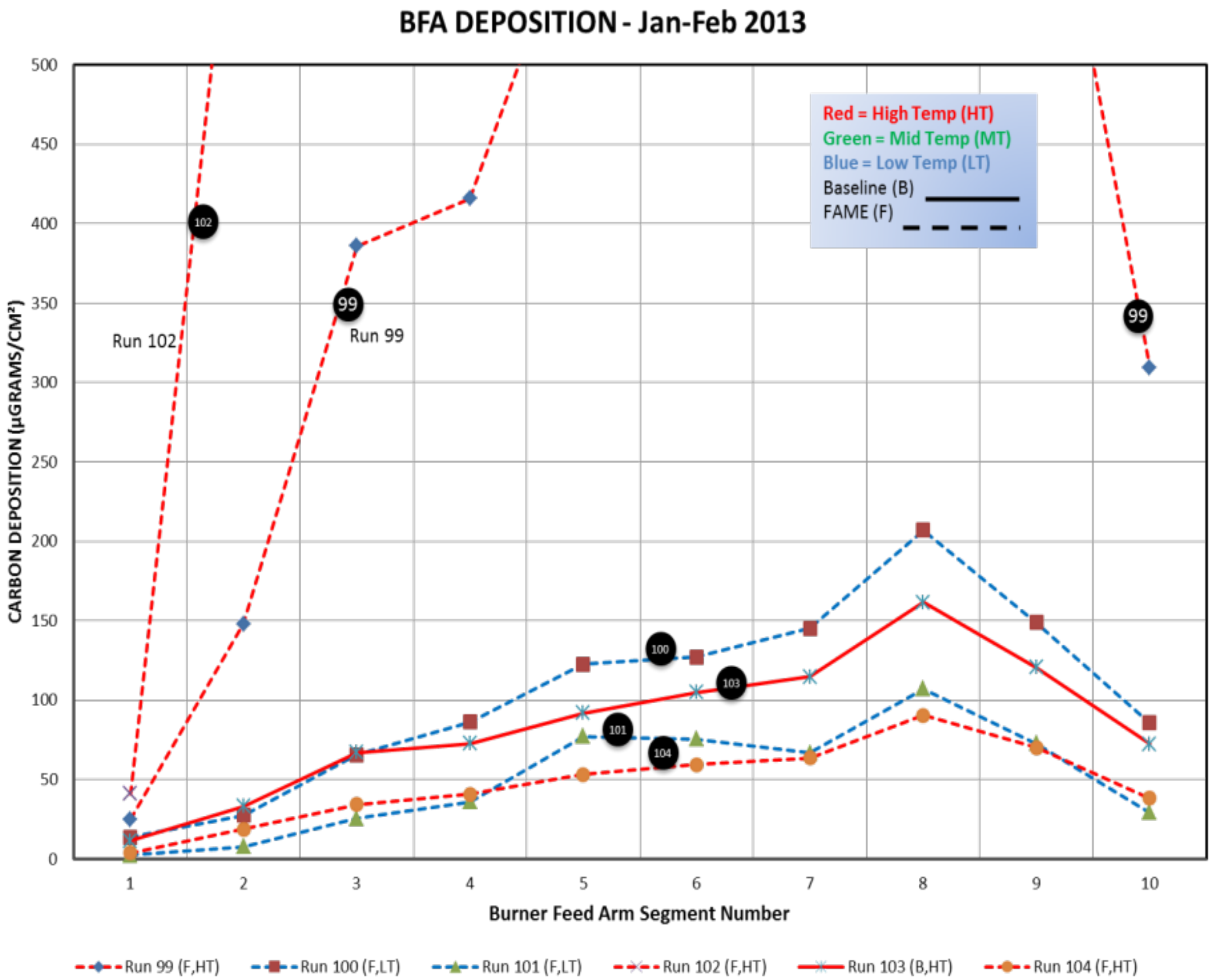


Figure 19 – BFA Deposition at All Temperatures For Baseline and Contaminated Fuel AFTER Baseline Fuel Breakpoint Degradation

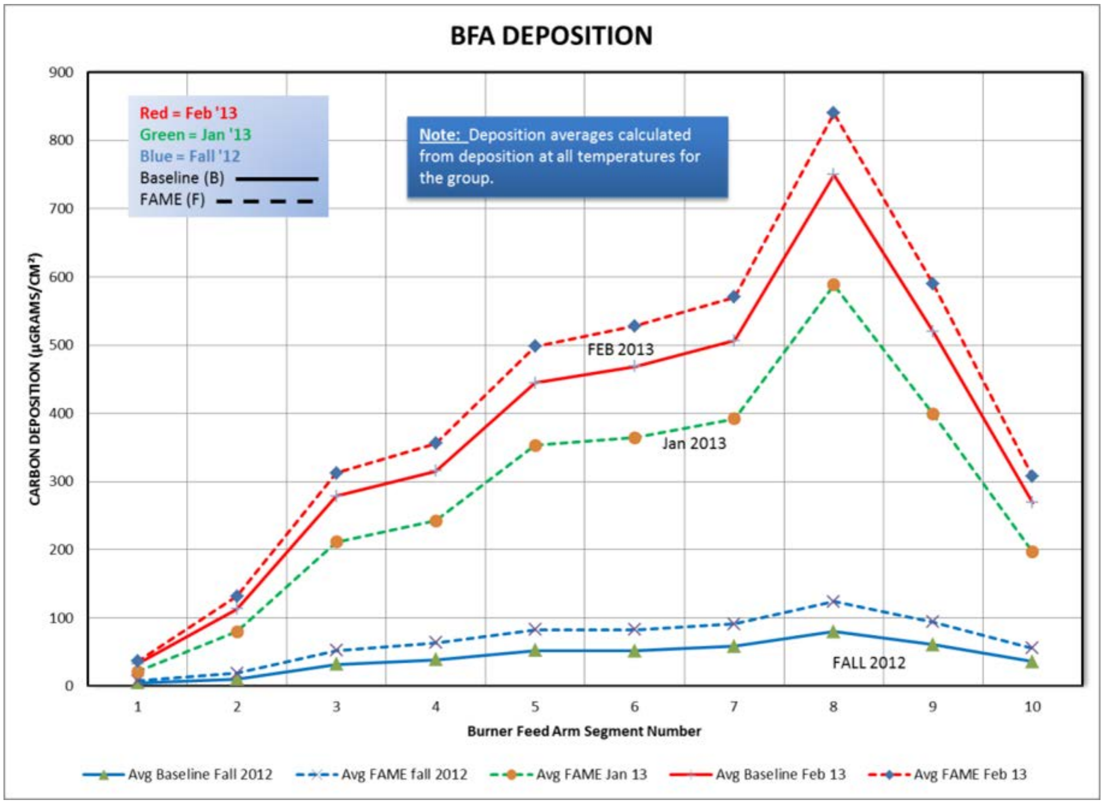


Figure 20 – Averaged BFA Deposition Across all Temperatures For Three Time Periods

5.6.2 Carbon Deposition –FCOC

Fuel-Cooled-Oil-Cooler carbon deposition was evaluated from the same perspective as the BFA data in order to see if the same trending from the BFA applied. Figures 21 through 24 are coinciding plots to Figures 17 through 20. As can be seen in these figures, FCOC and BFA reveal consistent results.

In these Figures, deposition seems to be increased for FAME-contaminated fuel in all test regimes. However, since there is evidence of a slight decrease in baseline fuel thermal stability as determined by JFTOT® Breakpoint, it becomes uncertain if this slight increase is due to FAME or to the deteriorated Breakpoint. Best case, the increase is indeed due to Breakpoint deterioration in which case it can be assumed that there is no impact from FAME. Worst case, where the deposition is wholly attributed to FAME, the increase is so slight (even though consistent) as to be within the repeatability of the ARSFSS test. In either case, the detrimental effect of FAME is negligible to nonexistent.

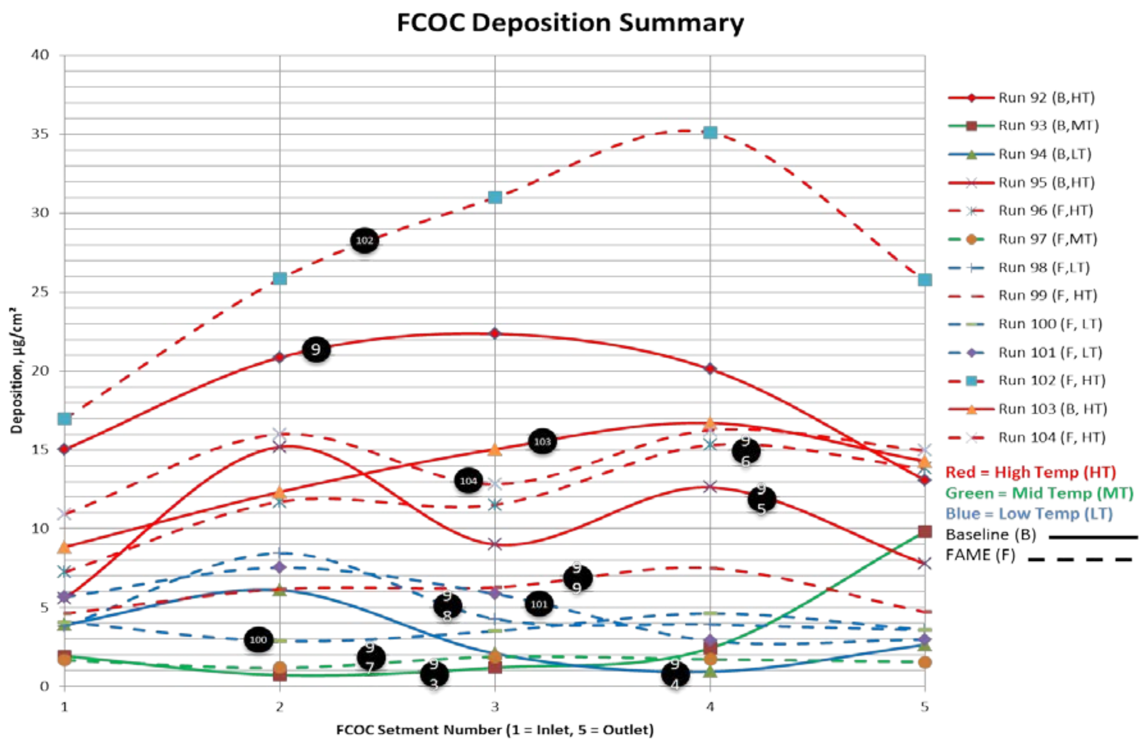


Figure 21 – Composite of All FCOC Deposition Data

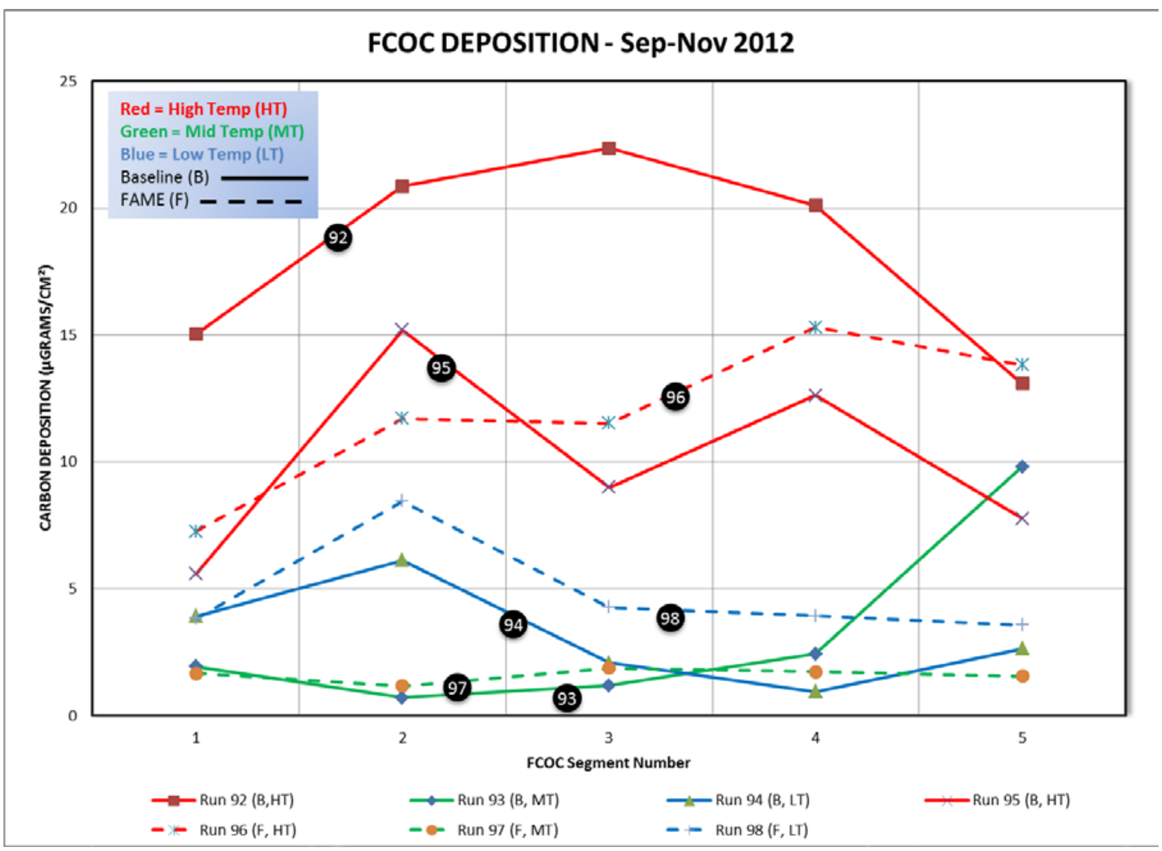


Figure 22 – FCOC Deposition at All Temperatures For Baseline and Contaminated Fuel PRIOR to Baseline Fuel Breakpoint Degradation

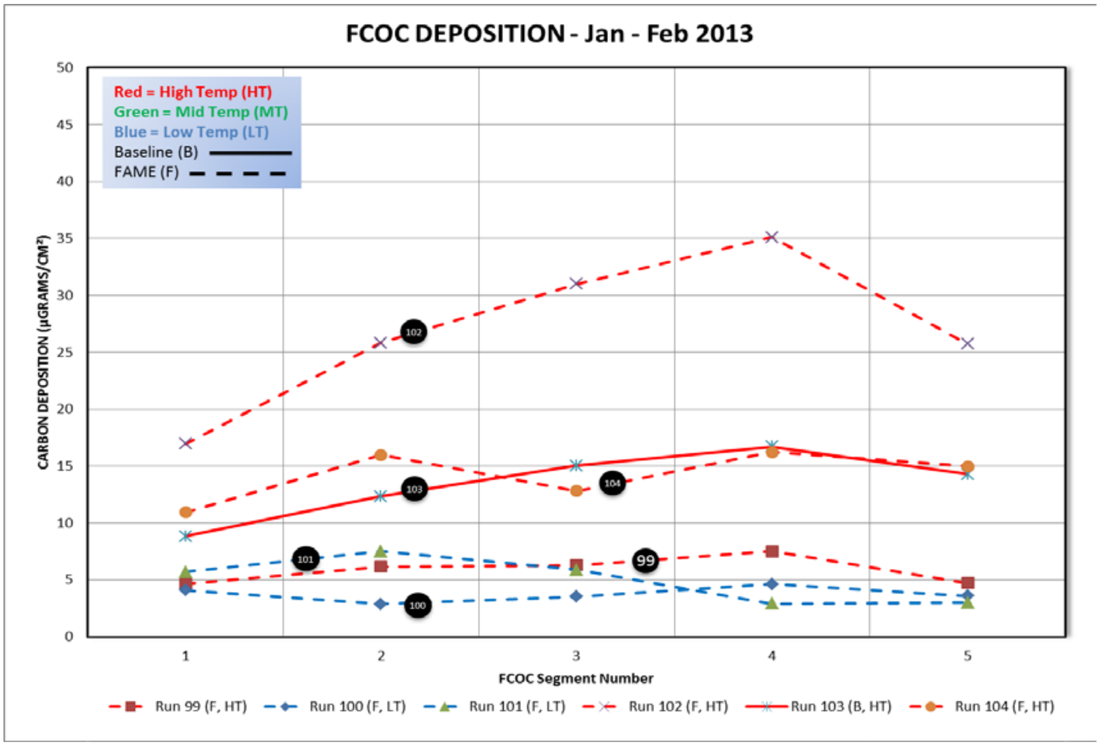


Figure 23 – FCOC Deposition at All Temperatures For Baseline and Contaminated Fuel AFTER Baseline Fuel Breakpoint Degradation

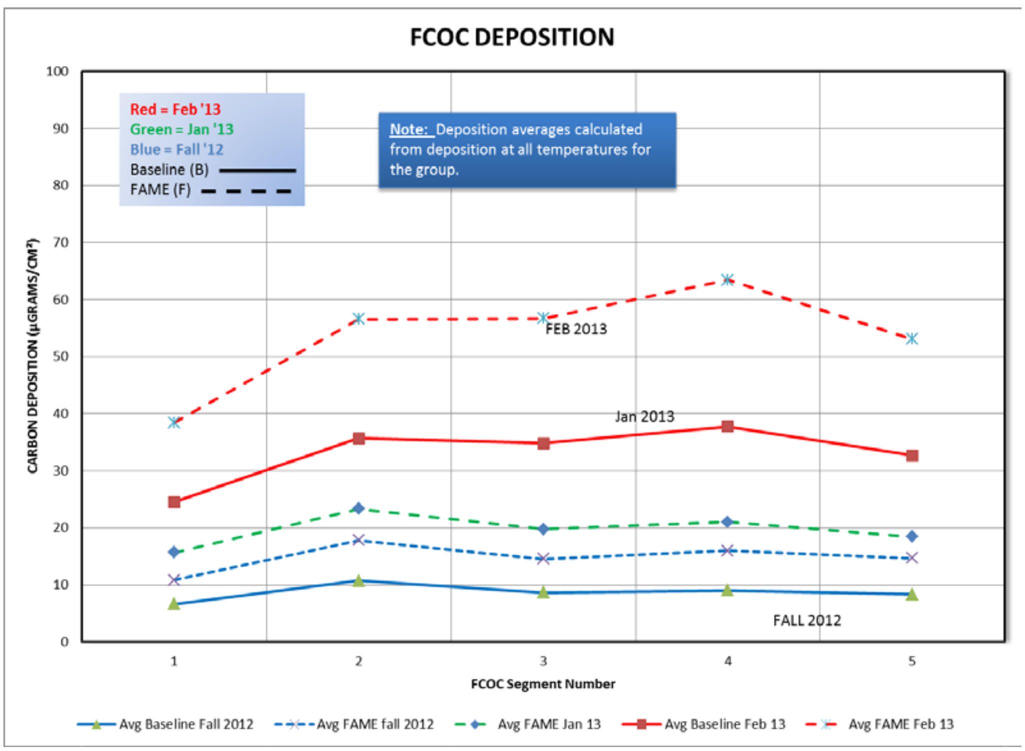


Figure 24 – Average FCOC Deposition Across All Temperatures For Three Time Periods

5.6.3 *Long Duration Switched Fuel (LDSF) Protocol*

For each GDTC run that is performed, BFA, FCOC and servo valve hardware components are new each time. While every effort is made to make sure replacement parts are a close to standard as possible, subtle differences between servo valves, BFA tubes and FCOC tubes still exist. Additionally, installation of these components necessitates shutting down the ARSFSS system, mechanical intrusion, reassembly and restarting. The subtle deviations from the build standards that results can manifest themselves in slight changes in heater settings and control parameters for the run. This is why each GDTC run starts with the first one or two missions being when all of the controls are adjusted and tweaked to meet the target run conditions. These subtle differences are completely consistent with differences from one engine to another and one airframe to another. As in the real world, these subtle differences can have an impact on deposition and/or temperature profiles even though the target run conditions may be exactly the same.

In looking at the data scatter for the BFA over the course of the program, a way was sought to negate these subtle differences in hardware and assembly and to find a way to look exclusively at deposition. Hence the concept of the Long Duration Switched Fuel protocol (see Appendix B). In this protocol, a series of missions are run as in the GDTC protocol using one fuel (in this case, the FAME-contaminated fuel). Throughout the LDSF run, deposition is monitored through BFA WWT temperature rise and fuels are switched. It must be noted that because fuels are switched without changing the servo valve or FDV hardware, measurements of hysteresis in these devices is meaningless. Carbon deposition measurements are also meaningless. The key data from this type of test is the WWT profile that results.

After completion of the GDTC runs (Runs 92 through104), a LDSF protocol run was initiated as Run 105. This run was eventually 204 missions long (over 400 hours of run time). Figure 25 shows a plot of BFA Maximum WWT for the HP Cruise mission segment for the 200+ missions executed.

The initial run conditions were set at the LT temperature profile conditions. These conditions were selected in hopes that the maximum WWT over the course of the run would not exceed ARSFSS safety limits. However, after 45 missions, there was no apparent WWT rise. The key to this test is to experience a WWT rise in 20 to 30 missions. After 45 missions with no WWT rise, the temperature profile was changed to the HT profile with a BFA WWT target of 500 °F. By mission 80, no upward slope in the BFA Max WWT was observed. At this time the BFA target WWT was increased to 510 °F while the FCOC bulk fuel inlet and outlet temperatures remained at the standard HT profile values. After an additional 30 missions, a rise in BFA WWT started to appear. Therefore, these temperature and flow conditions were locked in for the remainder of this run. From review of the prior data at the HT conditions, it was surprising that so small a WWT rise was observed in this test, especially when the fuel baseline breakpoint was degraded. This is further indication that for some reason this fuel seemed to be sensitive to deposition at these conditions in as much as sometimes the deposition was low and sometimes it was high.

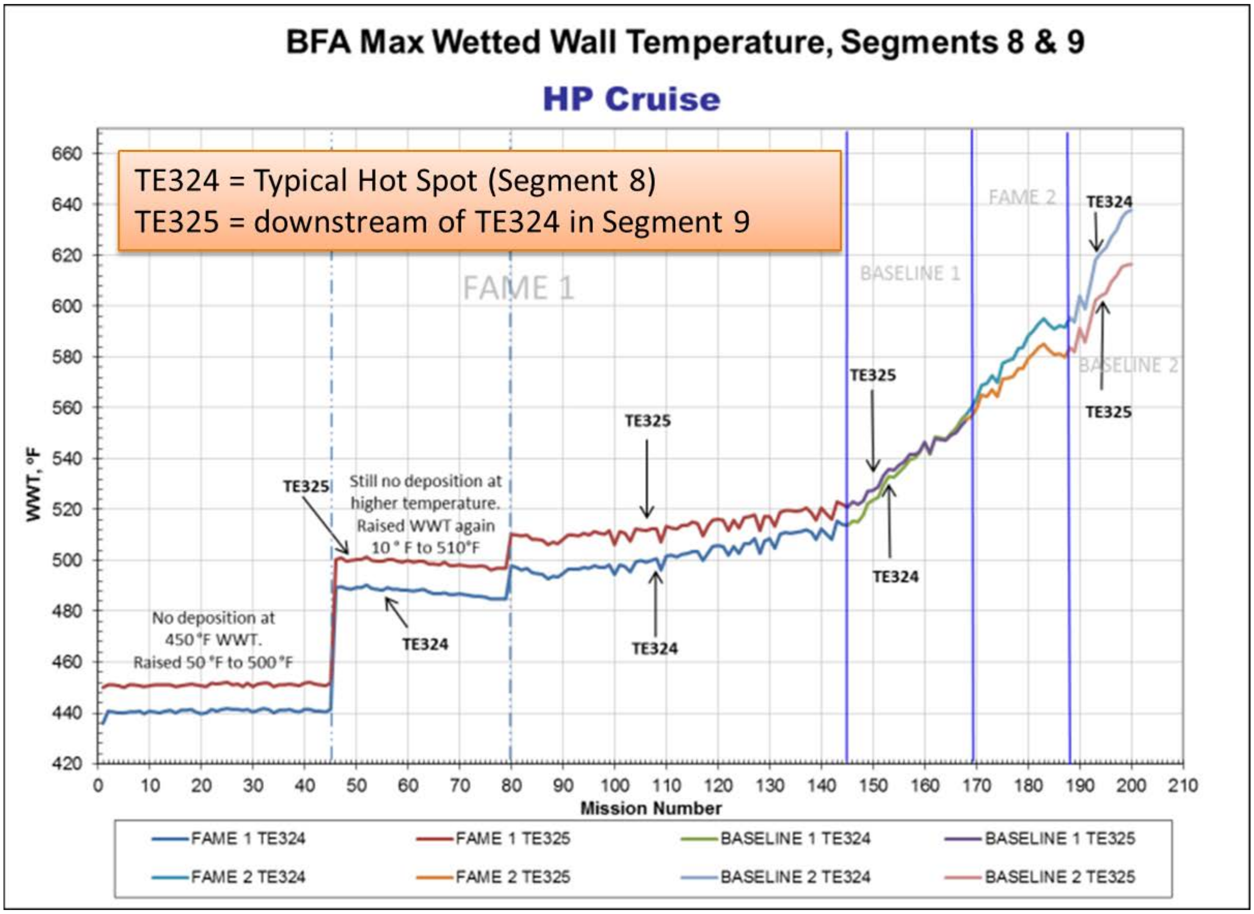


Figure 25 – Run 105 BFA WWT vs Mission Number – LDSF Testing Protocol

For Run 105 the starting fuel was the FAME-contaminated fuel so the first 145 missions were accomplished with this fuel. By Mission 145, a rise of about 12 °F had been observed for the maximum BFA WWT. Starting with Mission 146, the fuel was switched to baseline fuel. Measurements of FAME levels in the fuel leaving the test rig were down below 5 ppm by the time 3 missions were accomplished. During this baseline fuel part of the test, a significant rise in WWT was observed – approximately 26 °F over the course of 24 missions. Following Mission 169, the source fuel was switched back to the FAME-contaminated fuel. A rise in BFA WWT was again observed – approximately 35 °F over the course of 19 missions. After Mission 188, the fuel was switched to baseline fuel and the now familiar rise in BFA WWT exceeded 46 °F in just 16 missions. With this data in hand, the test run was terminated.

The challenge now became to determine if indeed we could tell a difference in the rate of deposition between baseline and FAME-contaminated fuel. A simple difference assessment was not applicable because it is normal for deposition in the AFSFSS over a long run to exhibit an 'exponential' behavior so the problem was now how to discern from a normally 'exponential' behavior and something else. This issue was resolved using data from Run 102.

In Run 102, the fuel (FAME-contaminated fuel under HT conditions) gave some enormous deposition – probably the highest deposition of any fuel ever evaluated on the AFSFSS. This magnitude of deposition is not 'typical' for fuels of the type used in this program (as evidenced by the balance of the program's data) so it is generally assumed that such results are anomalous and are the result of atypical hardware builds or perhaps even random fuel contamination issues.

The overall rise in BFA WWT for Run 102 was commensurate with the rise experienced in Run 105 both in shape and magnitude (see Figure 26). The general shape of this Run 102 BFA WWT curve was captured and overlaid on the Run 105 BFA WWT curve (See Figure 27). By comparing the shape of the Run 102 curve to the shape of the Run 105 curve in Figure 27, it is seen that the behavior that would have been anticipated from a material that negatively impacted fuel thermal stability (see Appendix B) is simply not present. This leads to the conclusion that the fuel switching did not have an impact on the BFA WWT rise which in turn leads to the conclusion that there is no obvious difference in deposition from a baseline FAME-sensitive fuel and FAME-contaminated fuel.

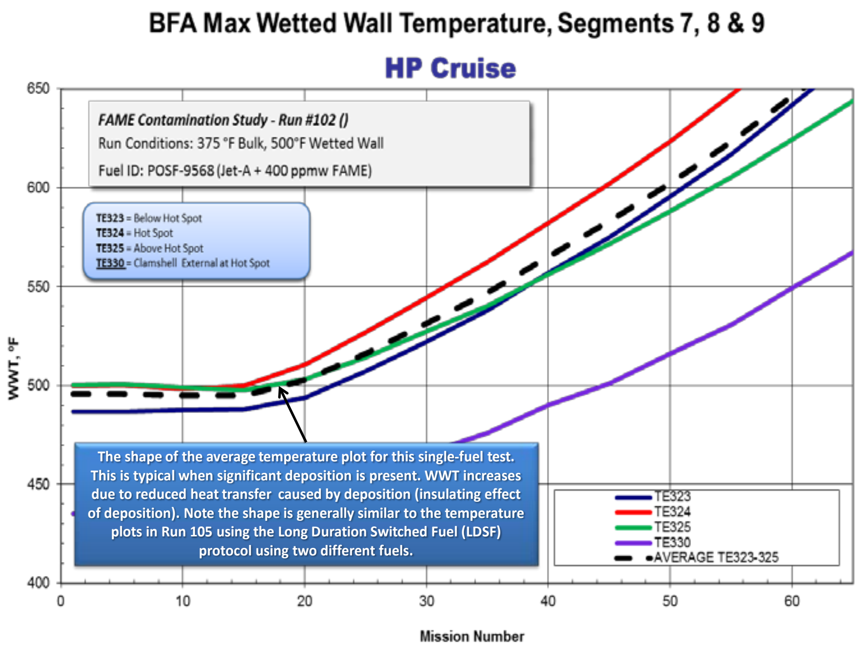


Figure 26 – General Shape of BFA WWT Curve for Run 102

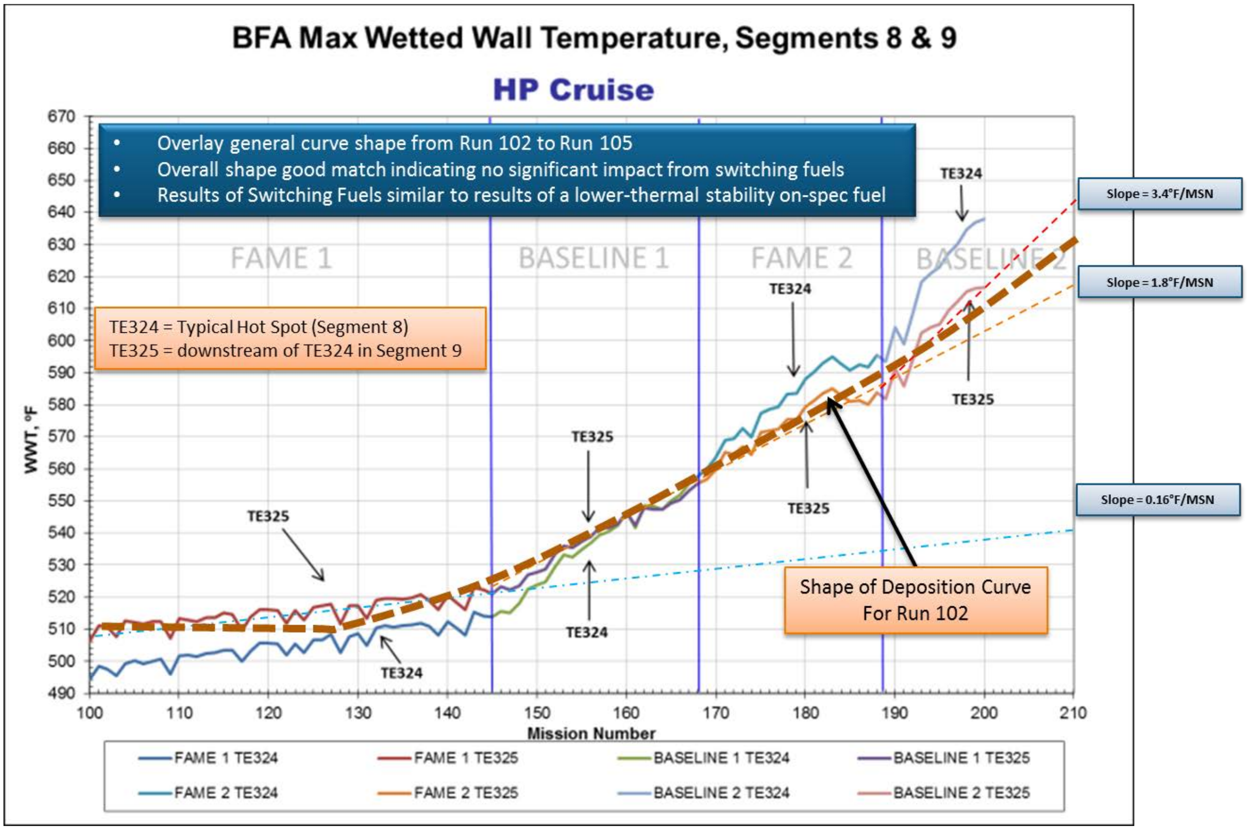


Figure 27 – Curve Shape of Run 102 Overlaid on BFA WWT Curve Run 105

5.6.4 Extended Duration Protocol

Once all of the planned GDTC missions were performed and the deposition data was observed to have some scatter without firm explanation, a different protocol was contrived to perhaps shed some light on the GDTC data. Consuming 900 gallons of fuel in each GDTC run, the ARSFSS is not well suited to parametric studies. In the past, the Extended Duration Thermal Stability Test rig would have been used to perform parametric studies to find the right test temperature profile to use in the ARSFSS. But since that rig is no longer available, just the QCM and JFTOT® Breakpoint are used. Discussions were therefore initiated to determine if there was a way to operate the ARSFSS in the pseudo-EDTST mode. If the run time and fuel consumption could be reduced, then it might be possible to perform some parametric studies and perhaps shed some more light on the GDTC data.

It was determined that indeed, the ARSFSS could be run in an EDTST-mode with low fuel flow rates and reduced operating time. Therefore a protocol was developed to run the ARSFSS at steady-state flow conditions with flow being 13.1 pounds per hour (PPH) main core flow (through the BFA) and a total of 26.2 PPH through the FCOC with 50 percent of that flow recirculated back to the ARSFSS tanks. Test time planned would be 72 hours. The EDTST flowed 1 gallon per how (GPH) through the main Heater section (BFA Equivalent) and 2 GPH through the Preheater section (FCOC Equivalent) with 1 GPH being recirculated back to the feed tank. The test duration for the EDTST was 96 hours.

This testing protocol was first initiated after Run 105 (LDSF protocol). These runs were designated Runs 106 and 107 with Run 106 being the baseline test and 107 being the FAME-contamination test. The test temperature profile for the initial baseline and FAME-contamination runs was the LT profile. In these two runs, no rise in BFA WWT was noted (Figure 28 and 29). This is most likely due to the low flow rate at which the test was run. Since no rise in BFA WWT was noted, the tests were re-run as Runs 90 and 91 with the HT profile. Based on the experience in Run 105, the BFA WWT was increased to 510 °F (266

°C). This modified HT profile was designated the HT+ profile. Run 90 was the baseline test and 91 being the FAME-contamination test. In Run 90, no BFA WWT rise was noted (Figure 30). However, in Run 91, a **reduction** in BFA WWT was noted (Figure 31). This is not inconsistent with prior experience. It has been observed in prior testing that even these relatively low concentrations of FAME can improve heat transfer characteristics leading to the fuel taking more heat away from the heated surface and lowering the surface temperature. Post-test BFA carbon deposition data revealed that deposition did occur in all four of these runs (Figure 32) despite the lack of BFA WWT rise for either the baseline or FAME-contamination test. Deposition in the FCOC was also determined for these four runs and as shown in Figure 33, there was no substantial change in deposition for baseline fuel versus FAME-contaminated fuel. While these tests did prove that the ARSFSS could be operated in this mode and deposition could be observed, it will remain to be seen if this protocol can be used reliably in the future.

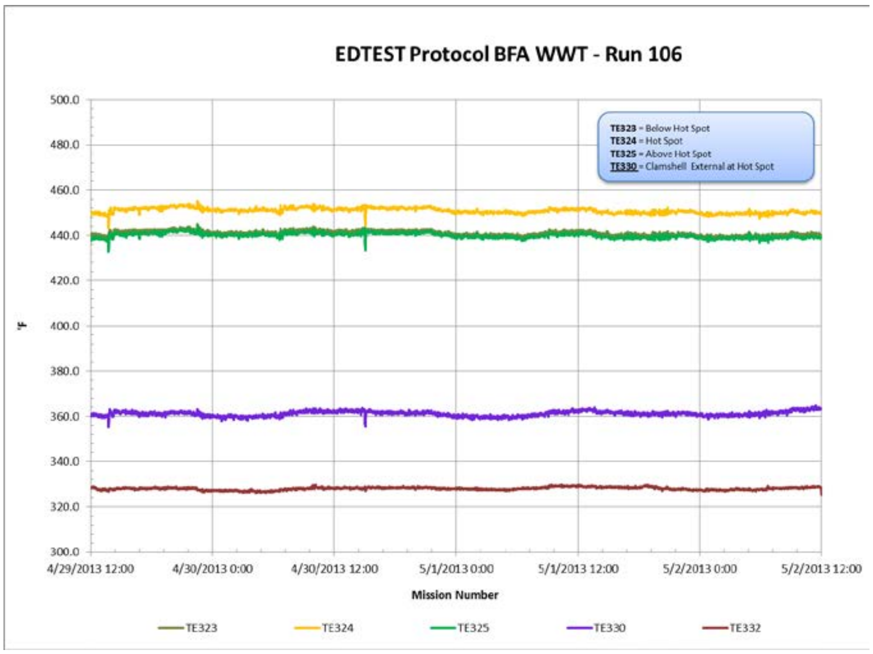


Figure 28 – BFA Temperatures Showing Steady Temperatures For Run 106

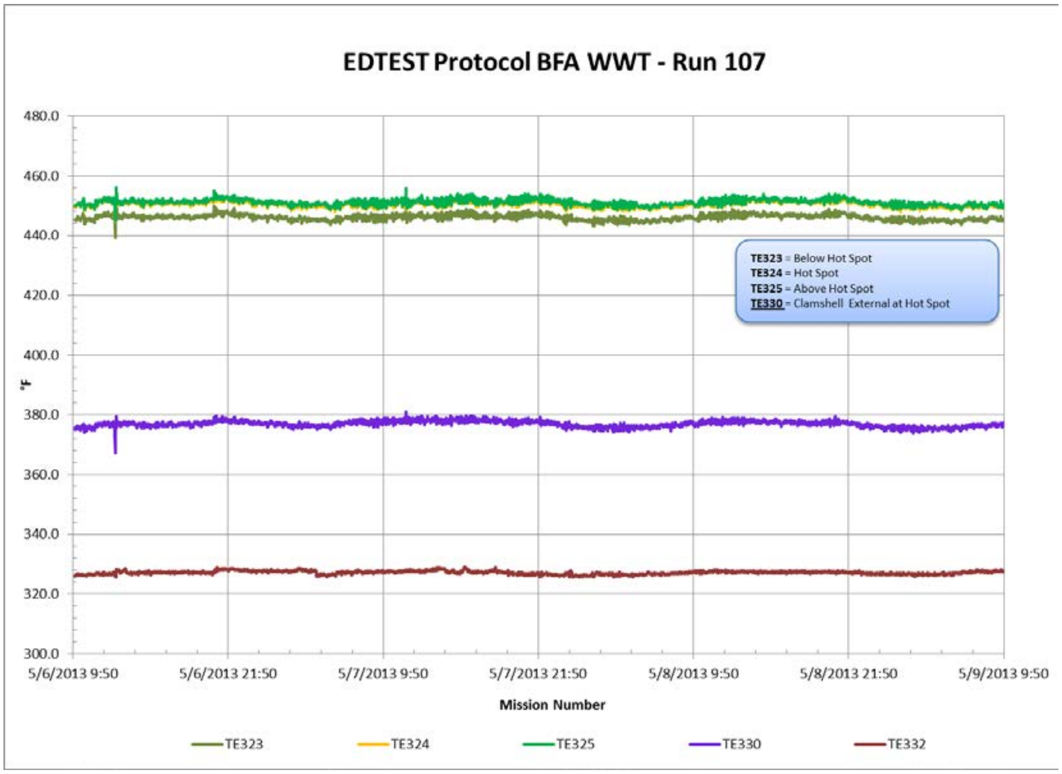


Figure 29 – BFA WWT – Run 107

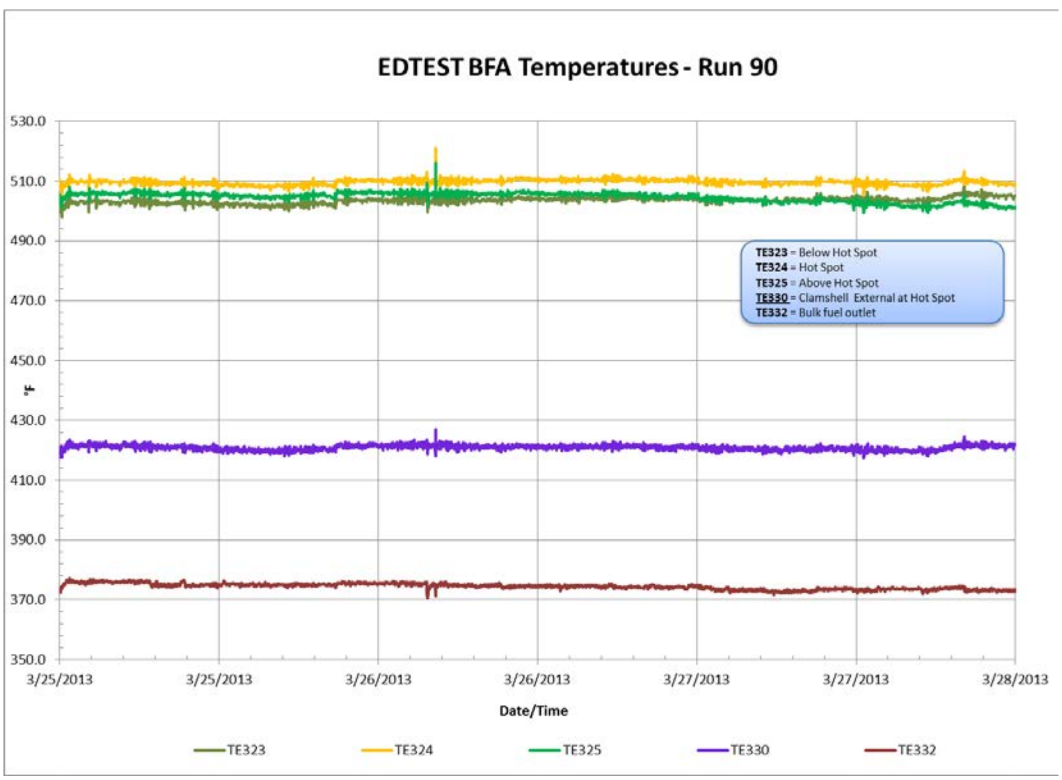


Figure 30 – BFA WWT – Run 90

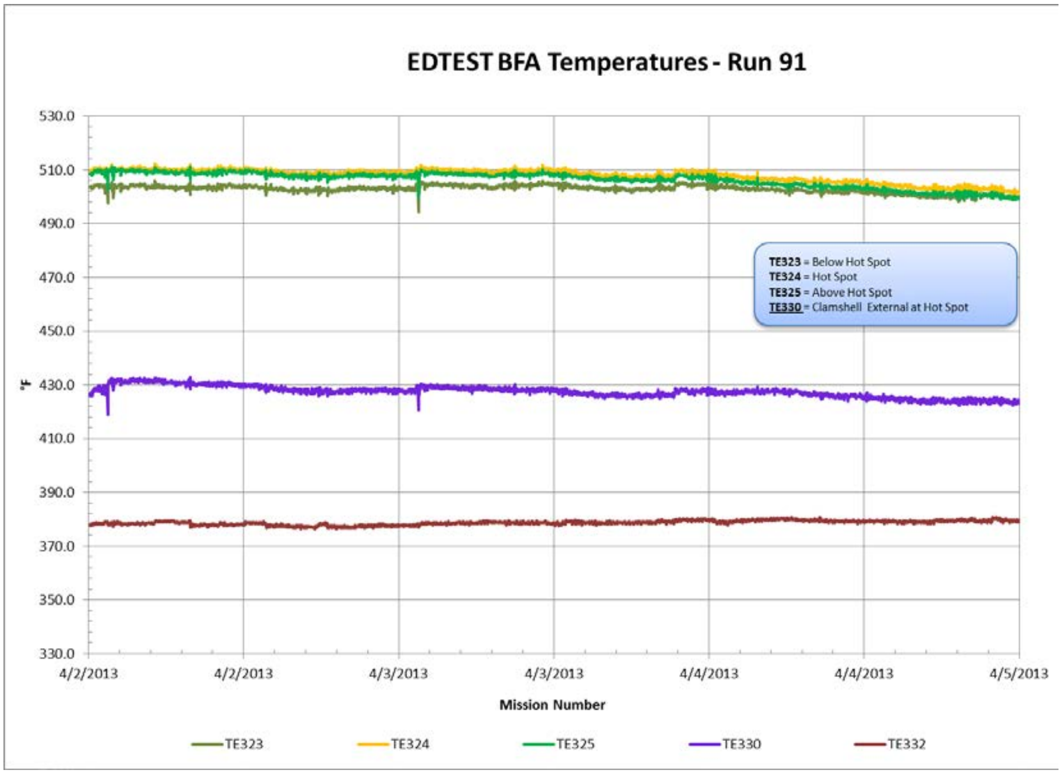


Figure 31 – BFA WWT – Run 91

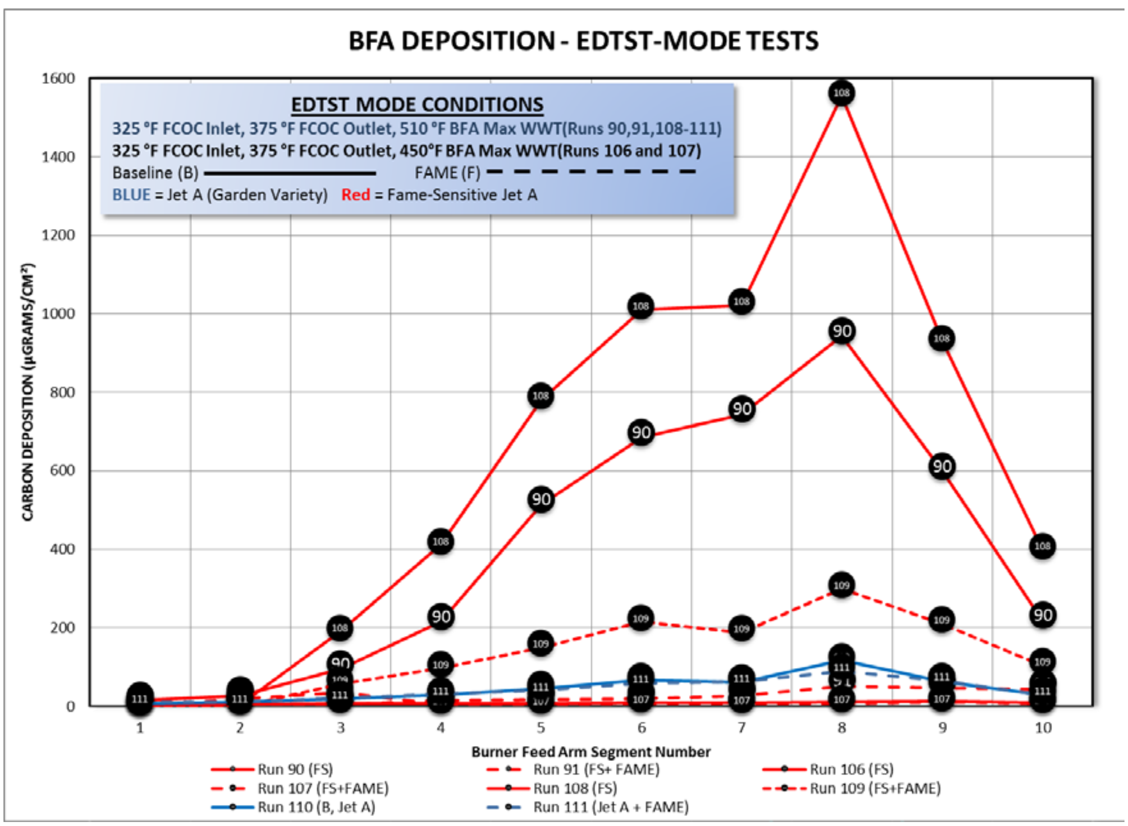


Figure 32 – Carbon Deposition in the BFA, EDTST Protocol

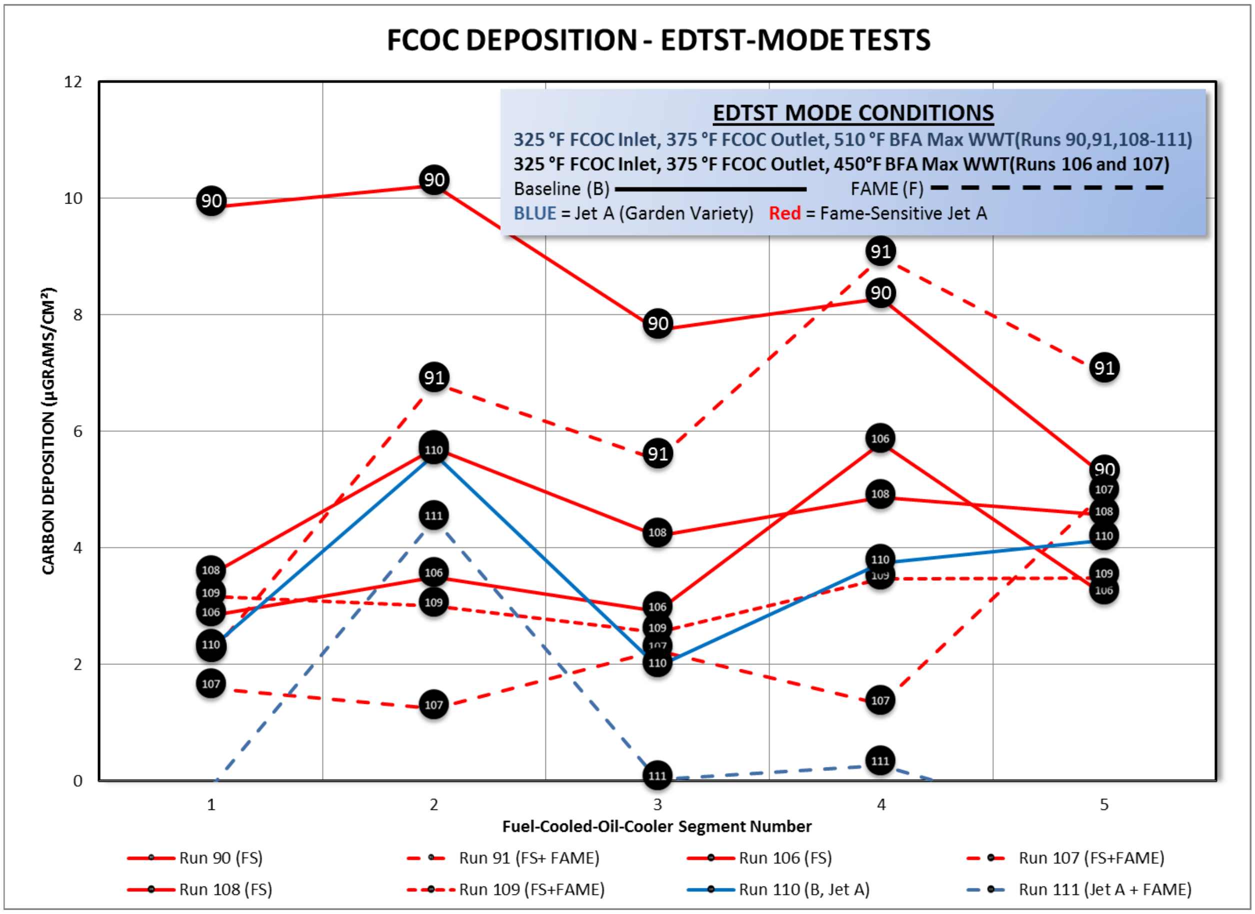


Figure 33 – Carbon Deposition in the FCOC, EDTST Protocol

5.7 Servo Valve Performance and Deposition

5.7.1 Mission Cycle Testing

Appendix D shows all of the hysteresis plots for the Servo Valve from Runs 92-104. In these plots, the blue line shows Differential Pressure vs. Flow data for the valve prior to the Run while the red line shows data for the valve AFTER the run. The spread between the blue lines indicates the inherent mechanical hysteresis of the valve. Any spread in the red lines beyond the 'baseline' spread of the blue lines is attributed to coke deposition inside the valve. For example, in Figure D-1 for Run 92, the plot shows a noticeable increase in the spread between the pre-test and post-test hysteresis lines. From Figures 17 and 18 in section 5.6, the reader will note that Run 92 was a relatively high-deposition run.

Figure D-2 shows similar hysteresis data for Run 93. In this plot, there is little if any hysteresis shift or spread for this Run. Also from Figures 17 and 18 in Section 5.6, the reader will note that the deposition for Run 93 was very low (comparatively).

Reviewing the hysteresis plots for Runs 93 through 98, recalling that these Runs were performed using the baseline (and contaminated) fuel PRIOR TO the noticed JFTOT® Breakpoint shift. For all of these hysteresis plots there is little if any shift in hysteresis between the pre- and post-test plots. Since these Runs encompass both baseline and FAME-contaminated Runs, the data tends to indicate that <u>there is no impact of FAME contamination on the performance of these valves.</u>

However, examining hysteresis plots for Runs 99 -104 (Figures D-8 through D-13), we start to notice an increase in post-test vs. pre-test hysteresis. This shift is particularly noticeable in Run 102 which was a Run that gave very high BFA deposition. Comparing hysteresis plots for baseline and FAME-contaminated fuels, based on just one baseline test, data might suggest that there is a slight degradation in valve hysteresis for FAME-contaminated fuel vs. baseline fuel. However, since D-12 (Run 103, BASELINE) and D-13 (Run 104, FAME) have very similar and very small hysteresis shifts, the data may not substantiate such a conclusion.

Assessing all the data from these plots tends to indicate that the shift in hysteresis may be more due to the shift in JFTOT® breakpoint than in any effect of the FAME contamination.

5.7.2 Extended Duration Thermal Stability Test (EDTST)Protocol

The EDTST protocol, as previously described, is a fixed flow rate protocol. Without changing flow rates which would normally involve operating the Servo Valve as an active component of the control process, one might expect that hysteresis in the Servo Valve might be increased since the valve is not 'stroking' as would be the case in normal operation and therefore not mechanically removing deposition. However, examination of the hysteresis plots for these Runs (90, 91, 106 and 107, Figures D-14-17)) does not support this expectation. Despite the high deposition in the BFA for Run 90 (See Figure 29, Section 5.6), the relatively low deposition in the FCOC for all of these Runs seems to be consistent with little or no shift in valve hysteresis (the Servo Valve is downstream of the FCOC and therefore is impacted by the temperature of the bulk fuel leaving the FCOC). However, there is a slight increase in hysteresis shift for Run 106 (FAME). But upon examination, it appears that the whole plot for post-test measurements has shifted away from the baseline pre-test plot. Normally the pre- and post-test plots would be either on top of one another (no hysteresis) or the post-test plot would straddle the pre-test plot indicating a hysteresis shift that is deposition-driven. However, when the post-test plot vs. pre-test plot shows a shift such as in Figure D-16, this is more indicative of a hysteresis shift caused by something mechanical in nature and not due to deposition. Therefore, it can be relatively clearly concluded that these Runs do not indicate any adverse effect of FAME on valve hysteresis.

5.8 FDV Performance and Deposition

5.8.1 Mission Cycle Testing

Appendix E shows all of the hysteresis plots for the FDV from Runs 92 through 104. As with the Servo Valve, in these plots, the blue line shows Differential Pressure vs. Flow data for the valve prior to the Run while the red line shows data for the valve AFTER the run. The spread between the blue lines indicates the inherent mechanical hysteresis of the valve. Any spread in the red lines beyond the baseline spread of the blue lines is attributed to coke deposition inside the valve. For example, in Figure E-1 for Run 92, the plot shows a noticeable increase in the spread between the pre-test and post-test hysteresis lines. From Figures 17 and 18 in section 5.6, the reader will note that Run 92 was a relatively high-deposition run.

Figure E-2 shows similar hysteresis data for Run 93. In this plot, there is only a small amount of hysteresis shift or spread for this Run. Also from Figures 14 and 15 in Section 5.6, the reader will note that the deposition for Run 93 was very low (comparatively).

Reviewing the FDV hysteresis plots for Runs 93 through 98, recalling that these Runs were performed using the baseline (and contaminated) fuel PRIOR TO the noticed JFTOT® Breakpoint shift. As with the Servo Valve, for all of these hysteresis plots there is little if any shift in hysteresis between the pre- and post-test plots. Since these Runs encompass both baseline and FAME-contaminated Runs, the data tends to indicate that there is no impact of FAME contamination on the performance of the FDV.

However, as with the discussion on the Servo Valve data, examining hysteresis plots for Runs 99 - 104 (Figures E-8 through E-13), we start to notice an increase in post-test vs. pre-test hysteresis. This shift is particularly noticeable in Run 102 which was a Run that gave very high BFA deposition. Comparing hysteresis plots for baseline and FAME-contaminated fuels, based on just one baseline test at the HT conditions (Run 103), data seems to suggest that there may be a slight degradation in FDV hysteresis for FAME-contaminated fuel vs. baseline fuel when the thermal stability of the non-contaminated fuel is inherently lower.

However, assessing all the data from these plots tends to indicate that the shift in hysteresis may be more due to the shift in JFTOT® breakpoint than in any effect of the FAME contamination

5.8.2 *Extended Duration Thermal Stability Test Protocol*

The EDTST protocol, as previously described, is a fixed flow rate protocol. Without changing flow rates which would normally involve operating the FDV, one could reasonably expect that hysteresis in the FDV might be increased since the valve is not 'stroking' as would be the case in normal operation and therefore not mechanically removing deposition. However, examination of the hysteresis plots for these Runs (90, 91, 106, and 107, Figures E-14-17)) does not support this expectation. These Runs seems to be consistent with little or no shift in valve hysteresis. However, there is a slight increase in hysteresis shift for Run 91 (FAME). But upon examination, it appears that there is a little more mechanically-induced hysteresis than already present in the upper flow ranges for the pre-test plot. Comparing the pre-test and post-test plots reveals that the deposition-induced hysteresis shift is not significantly greater for this Run than for the other three Runs at these conditions.

It can be reasonably concluded that these Runs do not indicate any adverse effect of FAME on FDV hysteresis.

5.9 Servo Valve, FDV and Nozzle Screen Simulator Deposition

5.9.1 *Mission Cycle Testing*

Appendix F is a compilation of comparison photograph of deposition in the Servo Valve (SV), FDV, and Nozzle Screen Simulator (NSS) for all Runs in this program except Run 105. Runs 92 through 104 were performed using the Mission Cycle Testing protocol. Runs 90, 91, 106 and 107 were performed using the EDTST protocol.

Reviewing the photos for Runs 92 through 104 (Figures F-1 through F-13), it can be generally concluded that there is no substantial visible deposition in any of these components with the exception of Run 102. When comparing visual deposition on components from Runs 92 through 98 vs. the visible deposition on components from Runs 99 through 104, there appears to be a very slight increase of tarnishing in the components from the later runs even though there is no substantial visible deposition on any of the components with the exception of Run 102 which was a run with abnormally high deposition. These visual results are largely substantiated in the hysteresis data for the SV and the FDV. Interestingly, sometimes parts exposed to the FAME-contaminated fuel appear visually cleaner than for the baseline fuel, for example Figures F-3 and F-9.

In previous sections of this report the decreased breakpoint temperature was discussed as potentially 'masking' some perhaps adverse effects of FAME. In most ARSFSS components, this lowering in Breakpoint of the baseline fuel is not readily observed. However, in Appendix R, Figures F-20 and F-21, a slight increase in staining in the Nozzle Screen is noticed for the baseline fuel at Breakpoint 275 °C when compared to the same baseline fuel at Breakpoint 285 °C. The same trend can be seen for the Nozzle Components in Appendix R, Figures F-22 and F-25.

Therefore, based solely on these visual results, there appears to be no impact of FAME on visible deposition for these components.

5.9.2 *Extended Duration Thermal Stability Test Protocol*

The EDTST protocol, as previously described, is a fixed flow rate protocol. Since the flow rate used in this protocol is a fairly low flow rate, it might be expected that visible deposition from this high temperature and low flow rate condition (resulting in high residence time and thus, high time-at-temperature conditions) might be more substantial than the visible deposition from the Mission Cycle testing conditions which has a some substantially higher flow rates and thus substantially lower residence and time-at-temperature times.

However, examination of the visual deposition plots for 90, 91, 106 and 107, Figures E-29 through D-32, does not support this expectation. These Runs seems to be consistent with little or no change in visible deposition. It can therefore be reasonably concluded that these photos do not indicate any adverse effect of FAME on visual deposition in either these components.

5.9.3 *HP Pump Filter Visual Inspection*

Figures G-1 and G-2 in Appendix G show the condition of the filters removed from the HP Pump for Runs 103, 104, 90, 91, 106, and 106. Figure G-1 shows a comparison of filters from Run 103 (baseline fuel run at the HT condition using the standard GDTC profile) and Run 104 which was the same except that it was for FAME-contaminated fuel. Figure G-2 shows a comparison for Runs 90, 91, 106 and 107 where were EDTST protocol runs at the HT+ condition.

While in most cases, these filters appear identical, In Run 104 the FAME-contaminated run shows a filter that looks slightly darker than its companion baseline run, Run 103. On the other hand, the filter from Run 90 (a baseline fuel run) seems to be slightly darker than its companion Run 91 filter.

However, what can be noted is that in all FAME-contaminated runs (91, 104, and 106), the photos show a thick brown 'gooey' deposit adhering to the metal end cap of the filter. Even though this material is present, there was no indication in any test parameters or performance indicating that this material was causing a detrimental problem. Further testing would be required to determine if this material is only present in FAME-contaminated runs and not Baseline runs.

5.9.4 *Post-Program EDTST Mode Additional Testing*

After the original release of the first draft of this report, AFRL decided to perform some additional testing using the ARSFSS EDTST-Mode protocol using the remaining FAME-Sensitive (FS) fuel and a typical garden variety (GV) Jet A. The purpose of this testing was to further vet the validity of the EDTST protocol and compare the testing in FS fuel to a GV fuel.

Additional runs were performed (see Table 7 below, which for the sake of comparison, contains results for all EDTST-mode tests). All of this testing was accomplished using the EDTST protocol. The temperature profile for this mode was 325 °F (163 °C) bulk fuel temperature to the inlet of the fuel-cooled-oil-cooler (FCOC), 375 °F (190 °C) bulk fuel temperature out of the FCOC and into the Burner Feed Arm (BFA) and 510 °F (266 °C) wetted-wall temperature in the BFA.

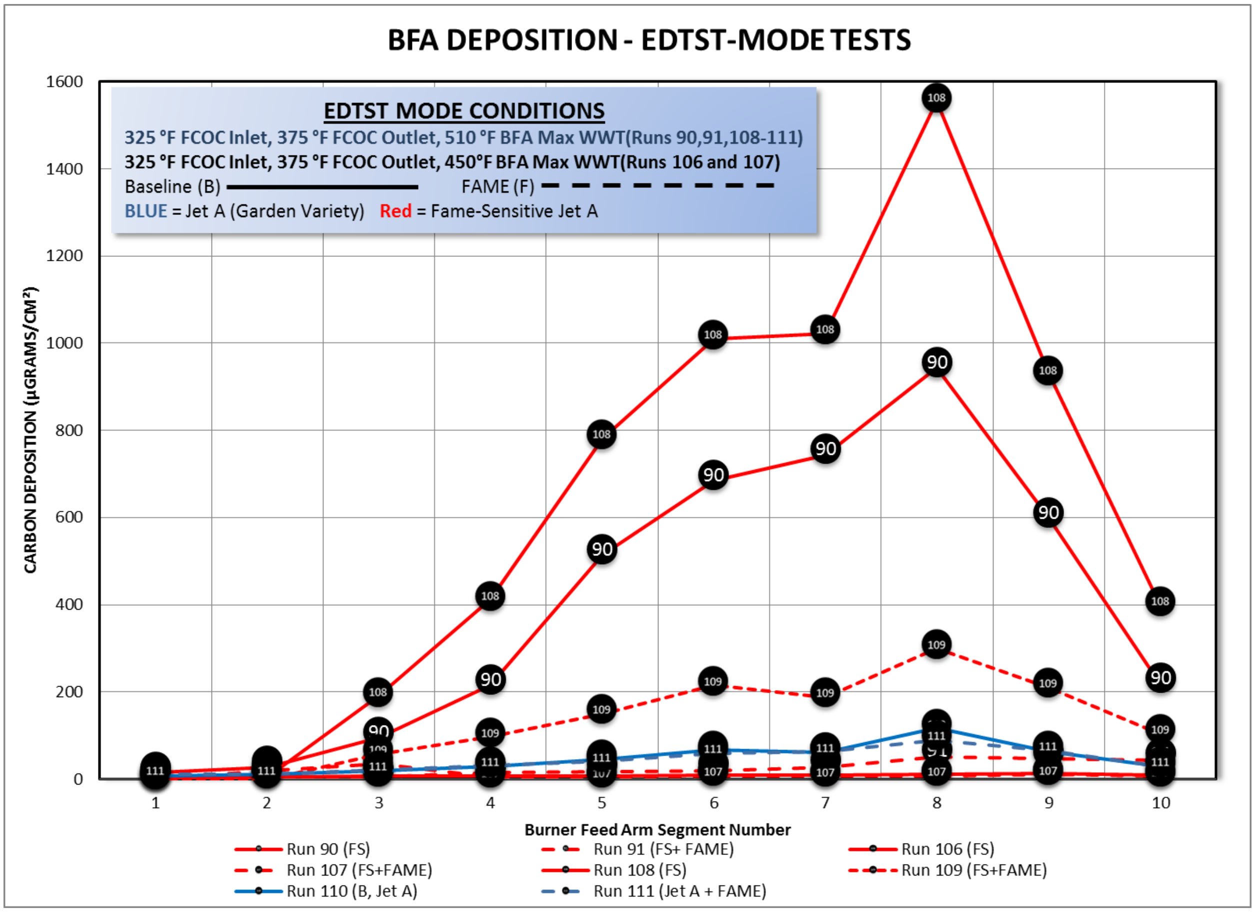
Table 7 – EDTST Mode Additional Testing

Carbon Deposition in EDSTS-Mode Tests									
Run	Fuel	DATE	FAME	Protocol	Bulk/Bulk/WWT °F	Total Effective Carbon Deposition (μg)		Maximum Effective Carbon Deposition (μg/cm²)	
						FCOC	BFA	FCOC	BFA
90	9326 – FS Fuel	25-Mar-13	N	EDTST	325/375/510	270.0	7,083.0	10.2	942.0
107	9326 – FS Fuel	6-May-13	N	EDTST	325/375/450	72.0	180.0	4.9	10.1
108	9326 – FS Fuel	6-Aug-13	N	EDTST	325/375/510	29.3	11,041.0	5.7	1,554.0
110	10325 – Jet A	26-Aug-13	N	EDTST	325/375/510	112.0	790.0	5.6	116.0
91	9326 – FS Fuel	2-Apr-13	Y	EDTST	325/375/510	83.0	430.0	8.9	51.3
106	9326 – FS Fuel	29-Apr-13	Y	EDTST	325/375/450	117.0	135.0	5.8	12.3
109	9326 – FS Fuel	19-Aug-13	Y	EDTST	325/375/510	101.0	2,317.0	3.4	299.0
111	10325 – Jet A	3-Sep-13	Y	EDTST	325/375/510	23.4	740.0	4.4	89.5

Since some time had elapsed since the previous testing using the FAME-sensitive Jet A, a sample of the fuel was evaluated for thermal stability breakpoint and compliance with Jet A specifications. In all regards except Electrical Conductivity, the fuel met Jet A specs. The JFTOT breakpoint was determined to be 285 °C (545 °F). Note that this breakpoint is higher than the final breakpoint in previous testing indicating that the fuel had 'recovered' its previous breakpoint rating.

Figure 34 shows a plot of carbon deposition for the BFA for the all of the EDTST-mode runs. Baseline FAME-sensitive fuel is the highest in deposition by a significant factor in two instances. When contaminated with FAME, the carbon deposition decreases significantly. In the typical Jet A (blue lines), there is no change in BFA deposition between baseline and contaminated fuel. As in previous testing in all protocols comparing the baseline fuel to the FAME-contaminated fuel, ARSFSS operators noted that slightly higher heater power settings were required to establish BFA and FCOC wetted wall conditions.

As mentioned in earlier sections of this report, this phenomenon was experienced by other researchers performing rig testing similar to the ARSFSS testing.



NOTE: Run 110 data lies UNDER Run 11 data

Figure 35 shows a plot of carbon deposition for the FCOC for the EDTST-mode runs. For all fuels at these EDTST-mode conditions, there is no discernible difference in deposition between baseline and contaminated typical Jet A fuel in the FCOC. Servo Valve and FDV Valve hysteresis plots for these four runs are presented in Appendix H to further confirm the results illustrated by the BFA and FCOC deposition plots. Photographs of Servo, FDV, and Nozzle Screen components are also presented in Appendix H – all of with further substantiate the carbon deposition plots.

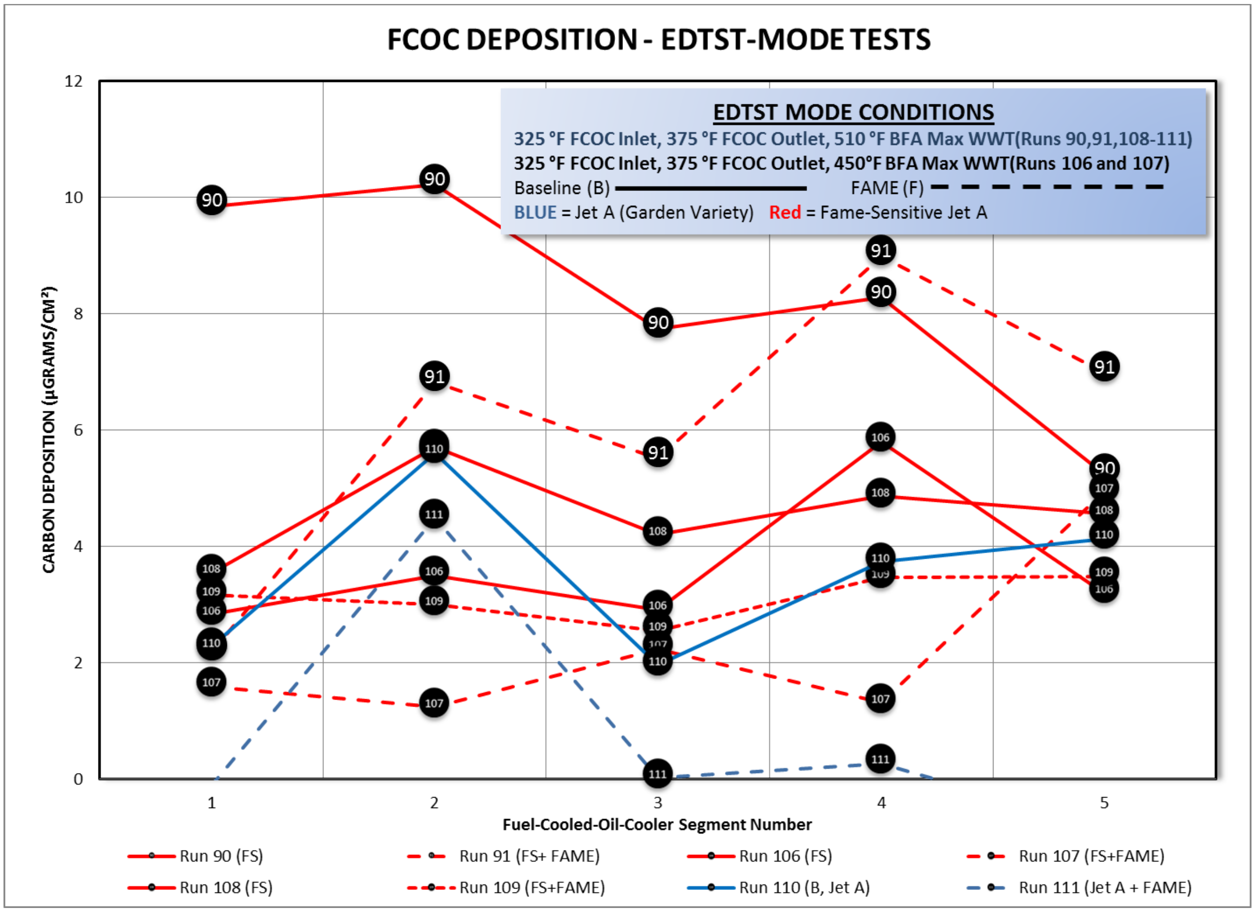


Figure 35 – FCOC Carbon Deposition in FAME-Sensitive and Typical Jet A

6.0 Discussion and Conclusions

Extensive testing has been accomplished on a single FAME-sensitive fuel using bench scale (JFTOT® and QCM) test devices as well as a rig-scale simulator using 3 different test method/simulation protocols. In a variety of measurements and visual assessments, there is no substantial indication that FAME contamination in fuel up to 400 ppm causes any substantial coke deposition in a variety of engine hardware components. Further the data does not indicate that there is any substantial degradation in performance or functionality of these components that would lead to service life or maintenance issues.

While some limited differences were observed between baseline and FAME-contaminated fuels, such variations may be more due to a change in overall thermal stability characteristics of the baseline fuel than to the FAME contamination. Also, the variations seen in the data are believed to be within the variance experience that is typical for testing accomplished using these devices and rig.

The only other differences between baseline and FAME runs were in the area of the HP Pump Filter. In this area, some additional deposition was noted on the fuel filter element caps for FAME runs only. This could be due to a high concentration of FAME material in the fuel undergoing some reactions in a low-flow/high residence time are of the filter bowl. However, additional work would need to be done to fully understand this phenomena and its impact on the assessment of this report. The filter elements themselves exhibit a range of colorations. While qualitative in nature, this does tend to demonstrate the lack of an obvious and discernible difference between baseline and FAME runs. This in itself supports the conclusions above.

The author would like to emphasize to the reader that testing was accomplished under worst-case conditions and that where there are slight differences between baseline and FAME run data, these were at the high temperature conditions that exceed the conditions present in current commercial engines. This supports the conclusions of this report, at least for commercial engines at 4X lower concentration (100 ppm) than testing in this program.

To substantiate the claim in this report that "the variations seen in the data are believed to be within the variance experience that is typical for testing accomplished using these devices and rig," the Energy Institute (EI) undertook a limited statistical analysis of two of the parameters measured by the ARSFSS – carbon deposition in the Burner Feed Arm (BFA) and carbon deposition in the FCOC. The letter report prepared from this statistical analysis by Alisdair Clark on behalf of the EI-JIP is being published as a part of the Final Report from Energy Institute, Joint Industry Program project seeking original equipment manufacturer (OEM) approval for 100 mg/Kg of fatty acid methyl ester (FAME) in aviation turbine fuel.

This letter report concluded that for the low and medium temperature test conditions (LT and MT), all the base fuel and base fuel + 400 ppm FAME deposits were within the repeatability of the test. The report further concluded that for the HT test condition, the base fuel and base fuel + 400 ppm FAME deposits were within the repeatability of the test with the exception of Runs 99 and 102 where the BFA deposits were outside test repeatability and greater than the three base fuel cases and Run 102 where one FCOC deposit was outside test repeatability and greater than the base fuel in one case. These statistical findings reinforce the conclusions of this report.

In conclusion, testing in this program does not indicate that the performance, operability or longevity of aircraft fuel systems and engine is adversely impacted through exposure of these components to FAME-contaminated fuel at up to 400 ppm. Therefore, it is even less likely that any adverse impact from FAME-contaminated fuel would be seen at 100 ppm. Therefore the presence of up to 100 ppm FAME contamination in even FAME-sensitive fuels should have a relatively benign impact on aircraft systems. However, it would be prudent to closely monitor for FAME contamination in fuels where the inherent thermal stability of the fuel is suspect as this contamination might exacerbate coking and deposition under these conditions.

Appendix A - Specification Analysis Results of Baseline Jet A As Received and Composited

AFPET LABORATORY REPORT
AFPA/PTPLA
2430 C Street
Building 70, Area B
Wright-Patterson AFB, OH 45433-7632

Lab Report No:2012LA40064001 Date Received:09/24/12 1028 hrs* Date Sampled: **
Cust Sample No:9326 Date Reported:10/01/12 1331 hrs* Protocol:FU-AVI-0036
JON: GENERAL FUND

Sample Submitter:
AFRL/RZPF
1790 Loop Road N
Bldg 490
Wright-Patterson AFB, OH 45433

Reason for Submission: AFRL Research
Product: Aviation Turbine Fuel, Kerosene
Specification: ASTM D 1655 - 12 Grade:Jet A

Qty Submitted: 2 gal
Batch/Lot/Origin: JET A

Method	Test	Min	Max	Result	Fail
ASTM D 3241 - 11a	Thermal Stability @ 290°C				
	Tube Deposit Rating, Visual			1A	X
	Change in Pressure (mmHg)			0	
ASTM D 3241 - 11a	Thermal Stability @ 280°C				
	Tube Deposit Rating, Visual			1	
	Change in Pressure (mmHg)			0	
ASTM D 3241 - 11a	Thermal Stability Breakpoint				
	Tube Deposit Rating, Visual			1	
	Change in Pressure (mmHg)			0	
	Breakpoint (°C)			285	
MIL-STD-3004C	Appearance			Pass	
ASTM D 3242 - 11	Total Acid Number (mg KOH/g)		0.10	0.00	
ASTM D 1319 - 10	Aromatics (% vol)		25	21	
ASTM D 3227 - 04a	Mercaptan Sulfur (% mass)		0.003	0.002	
ASTM D 4294 - 10	Total Sulfur (% mass)		0.30	0.06	
ASTM D 86 - 11b	Distillation				
	10% Recovered (°C)		205	164	
	20% Recovered (°C)	Report Only		171	
	50% Recovered (°C)	Report Only		194	
	90% Recovered (°C)	Report Only		246	
	End Point (°C)		300	269	
	Residue (% vol)		1.5	1.3	
	Loss (% vol)		1.5	0.5	
ASTM D 56 - 05	Flash Point (°C)	38		43	
ASTM D 4052 - 11	Density @ 15°C (kg/m³)	775	840	805	
ASTM D 5972 - 05e1	Freezing Point (°C)		-40	-54	
ASTM D 445 - 12	Viscosity @ -20°C (mm²/s)		8.0	3.8	
ASTM D 1322 - 08	Smoke Point				
	Smoke Point (w/allowable Naphthalenes) (mm)	18		20	
ASTM D 1840 - 07	Naphthalenes (% vol)		3.0	1.2	
ASTM D 130 - 10	Copper Strip Corrosion (2 h @ 100°C)	1 (Max)		1a	
ASTM D 3241 - 11a	Thermal Stability @ 260°C				
	Change in Pressure (mmHg)		25	0	
	Tube Deposit Rating, Visual	<3 (Max)		1	
ASTM D 381 - 12	Existent Gum (mg/100 mL)		7	<1	
ASTM D 1094 - 07	Water Reaction Interface Rating	1b (Max)		1	
ASTM D 3948 - 11	WSIM	70		99	
ASTM D 2624 - 09	Conductivity (pS/m)	50	600	0	X
ASTM D 5001 - 10	Lubricity Test (BOCLE) Wear Scar (mm)	Report Only		0.66	
MIL-DTL-83133H	Filtration Time (min)			3	

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AFPET LABORATORY REPORT
AFPA/PTPLA
2430 C Street
Building 70, Area B
Wright-Patterson AFB, OH 45433-7632

Lab Report No:2012LA40064001 Date Received:09/24/12 1028 hrs* Date Sampled: **
Cust Sample No:9326 Date Reported:10/01/12 1331 hrs* Protocol:FU-AVI-0036
JON: GENERAL FUND

Sample Submitter:
AFRL/RZPF
1790 Loop Road N
Bldg 490
Wright-Patterson AFB, OH 45433

Reason for Submission: AFRL Research
Product: Aviation Turbine Fuel, Kerosene
Specification: ASTM D 1655 - 12 Grade:Jet A

Qty Submitted: 2 gal
Batch/Lot/Origin: JET A

Method	Test	Min	Max	Result	Fail
ASTM D 7171 - 05	Hydrogen Content by NMR (% mass)			13.8	
ASTM D 4809 - 09a	Net Heat of Combustion (MJ/kg)			43.0	
ASTM D 5452 - 08	Particulate Matter (mg/L)			0.3	

Dispositions:
For information purposes only.

Approved By	Date
David Craycroft, Lead Chemist \\SIGNED\\	10/01/2012*

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amanda.rowton@wpafb.af.mil, david.craycroft@wpafb.af.mil, donald.minus@wpafb.af.mil, janet.stewart2@wpafb.af.mil, janet.swartz@wpafb.af.mil, jennifer.engelman@wpafb.af.mil, linda.shafer@wpafb.af.mil, rhonda.cook.ctr@wpafb.af.mil, richard.wilkes@wpafb.af.mil

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AFPET LABORATORY REPORT
AFPA/PTPLA
2430 C Street
Building 70, Area B
Wright-Patterson AFB, OH 45433-7632

Lab Report No:2013LA42145001	Date Received:01/25/13 1603 hrs*	Date Sampled: **
Cust Sample No:9326	Date Reported:01/31/13 1526 hrs*	Protocol:FU-AVI-0036
JON: GENERAL FUND		

Sample Submitter:
AFRL/RZPF
1790 Loop Road N
Bldg 490
Wright-Patterson AFB, OH 45433

Reason for Submission: AFRL Research
Product: Aviation Turbine Fuel, Kerosene
Specification: ASTM D 1655 - 12 Grade:Jet A

Qty Submitted: 3 gal
Batch/Lot/Origin: JET A

Method	Test	Min	Max	Result	Fail
ASTM D 2622 - 10	Sulfur (% mass)		0.30	0.055	
ASTM D 4809 - 09ae1	Net Heat of Combustion (MJ/kg)	42.8		42.9	
ASTM D 3242 - 11	Total Acid Number (mg KOH/g)		0.10	0.002	
ASTM D 1319 - 10	Aromatics (% vol)		25	22	
ASTM D 3227 - 04a	Mercaptan Sulfur (% mass)		0.003	0.002	
ASTM D 86 - 11b	Distillation				
	10% Recovered (°C)		205	168	
	20% Recovered (°C)	Report Only		173	
	50% Recovered (°C)	Report Only		194	
	90% Recovered (°C)	Report Only		245	
	End Point (°C)		300	269	
	Residue (% vol)		1.5	1.2	
	Loss (% vol)		1.5	0.8	
ASTM D 56 - 05	Flash Point (°C)	38		42	
ASTM D 4052 - 11	Density @ 15°C (kg/m³)	775	840	805	
ASTM D 5972 - 05e1	Freezing Point (°C)		-40	-54	
ASTM D 445 - 12	Viscosity @ -20°C (mm²/s)		8.0	3.8	
ASTM D 1322 - 12	Smoke Point				
	Smoke Point (w/allowable Naphthalenes) (mm)	18		22	
ASTM D 1840 - 07	Naphthalenes (% vol)		3.0	1.2	
ASTM D 130 - 12	Copper Strip Corrosion (2 h @ 100°C)	1 (Max)		1a	
ASTM D 3241 - 11a	Thermal Stability @ 280°C				
	Tube Deposit Rating, Visual	<3 (Max)		1A	X
	Change in Pressure (mmHg)		25	0	
ASTM D 3241 - 11a	Thermal Stability @ 290°C				
	Tube Deposit Rating, Visual	<3 (Max)		>4A	X
	Change in Pressure (mmHg)		25	0	
ASTM D 381 - 12	Existent Gum (mg/100 mL)		7	2	
ASTM D 1094 - 07	Water Reaction Interface Rating	1b (Max)		1	
ASTM D 3948 - 11	WSIM	70		99	
ASTM D 5006 - 11	FSII (% vol)	Report Only		0.00	
ASTM D 2624 - 09	Conductivity (pS/m)	50	600	0	X
MIL-DTL-83133H w/Amd 1	Filtration Time (min)			4	
ASTM D 7171 - 05	Hydrogen Content by NMR (% mass)			13.7	
ASTM D 1319 - 10	Olefins (% vol)			1.1	
ASTM D 5452 - 12	Particulate Matter (mg/L)			0.2	
ASTM D 3241 - 11a	Thermal Stability Breakpoint				
	Tube Deposit Rating, Visual			1	
	Change in Pressure (mmHg)			0	

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AFPET LABORATORY REPORT
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Wright-Patterson AFB, OH 45433-7632

Lab Report No:2013LA42145001 | Date Received:01/25/13 1603 hrs* | Date Sampled: **
Cust Sample No:9326 | Date Reported:01/31/13 1526 hrs* | Protocol:FU-AVI-0036
JON: GENERAL FUND

Sample Submitter:
AFRL/RZPF
1790 Loop Road N
Bldg 490
Wright-Patterson AFB, OH 45433

Reason for Submission: AFRL Research
Product: Aviation Turbine Fuel, Kerosene
Specification: ASTM D 1655 - 12 Grade:Jet A

Qty Submitted: 3 gal
Batch/Lot/Origin: JET A

Method	Test	Min	Max	Result	Fail
	Breakpoint (°C)			275	

Dispositions:
For information purposes only.

Approved By	Date
Amanda Rowton \\SIGNED\\	01/31/2013*

This report was electronically delivered to:
amanda.rowton@wpafb.af.mil, donald.minus@wpafb.af.mil, gordon.walker@wpafb.af.mil, jennifer.engelman@wpafb.af.mil, linda.shafer@wpafb.af.mil, michael.thiede@wpafb.af.mil, rhonda.cook.ctr@wpafb.af.mil, timothy.mudry@wpafb.af.mil

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AFPET LABORATORY REPORT
AFPA/PTPLA
2430 C Street
Building 70, Area B
Wright-Patterson AFB, OH 45433-7632

Lab Report No:2013LA42484001	Date Received:02/14/13 0646 hrs*	Date Sampled: 02/12/2013**
Cust Sample No:POSF 9326 RUN 103	Date Reported:02/15/13 1356 hrs*	Protocol:FU-AVI-0036
JON: GENERAL FUND		

Sample Submitter:
Rhonda Cook
AFRL/RZPF
1790 Loop Road N
Bldg 490
Wright-Patterson AFB, OH 45433

Reason for Submission: AFRL Research
Product: Aviation Turbine Fuel, Kerosene
Specification: ASTM D 1655 - 12 Grade:Jet A

Qty Submitted: 2 gal

Method	Test	Min	Max	Result	Fail
ASTM D 3241 - 11a	Thermal Stability Breakpoint				
	Tube Deposit Rating, Visual			1	
	Change in Pressure (mmHg)			0	
	Breakpoint (°C)			275	
ASTM D 3241 - 11a	Thermal Stability @ 280°C				
	Tube Deposit Rating, Visual		<3 (Max)	1A	X
	Change in Pressure (mmHg)		25	0	

Dispositions:
For information purposes only.

Approved By	Date
Miguel Acevedo, Chief \\SIGNED\\	02/15/2013*

This report was electronically delivered to:
amanda.rowton@wpafb.af.mil, donald.minus@wpafb.af.mil, linda.shafer@wpafb.af.mil, michael.thiede@wpafb.af.mil, miguel.acevedo@wpafb.af.mil, rhonda.cook.ctr@wpafb.af.mil, timothy.mudry@wpafb.af.mil

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** Date as provided by customer

AFPET LABORATORY REPORT
AFPA/PTPLA
2430 C Street
Building 70, Area B
Wright-Patterson AFB, OH 45433-7632

Lab Report No:2013LA42771001	Date Received:03/04/13 1023 hrs*	Date Sampled: **
Cust Sample No:9326	Date Reported:03/14/13 0857 hrs*	Protocol:FU-AVI-0036
JON: GENERAL FUND		

Sample Submitter:
AFRL/RZPF
1790 Loop Road N
Bldg 490
Wright-Patterson AFB, OH 45433

Reason for Submission: AFRL Research
Product: Aviation Turbine Fuel, Kerosene
Specification: ASTM D 1655 - 12 Grade:Jet A

Qty Submitted: 2 gal
Batch/Lot/Origin: JET A

Method	Test	Min	Max	Result	Fail
ASTM D 2622 - 10	Sulfur (% mass)		0.30	0.06	
ASTM D 3242 - 11	Total Acid Number (mg KOH/g)		0.10	0.003	
ASTM D 1319 - 10	Aromatics (% vol)		25	22	
ASTM D 3227 - 04a	Mercaptan Sulfur (% mass)		0.003	0.002	
ASTM D 86 - 11b	Distillation				
	10% Recovered (°C)		205	166	
	20% Recovered (°C)	Report Only		172	
	50% Recovered (°C)	Report Only		194	
	90% Recovered (°C)	Report Only		244	
	End Point (°C)		300	269	
	Residue (% vol)		1.5	1.4	
	Loss (% vol)		1.5	0.5	
ASTM D 56 - 05	Flash Point (°C)	38		44	
ASTM D 4052 - 11	Density @ 15°C (kg/m³)	775	840	805	
ASTM D 5972 - 05e1	Freezing Point (°C)		-40	-53	
ASTM D 445 - 12	Viscosity @ -20°C (mm²/s)		8.0	3.8	
ASTM D 1322 - 12e1	Smoke Point				
	Smoke Point (w/allowable Naphthalenes) (mm)	18		22	
ASTM D 1840 - 07	Naphthalenes (% vol)		3.0	1.2	
ASTM D 130 - 12	Copper Strip Corrosion (2 h @ 100°C)		1 (Max)	1b	
ASTM D 3241 - 11a	Thermal Stability @ 275°C				
	Tube Deposit Rating, Visual		<3 (Max)	1	
	Change in Pressure (mmHg)		25	0	
ASTM D 3241 - 11a	Thermal Stability @ 285°C				
	Tube Deposit Rating, Visual		<3 (Max)	<4	X
	Change in Pressure (mmHg)		25	0	
ASTM D 381 - 12	Existent Gum (mg/100 mL)		7	1	
ASTM D 1094 - 07	Water Reaction Interface Rating		1b (Max)	1	
ASTM D 5006 - 11	FSII (% vol)	Report Only		0.00	
ASTM D 2624 - 09	Conductivity (pS/m)	50	600	3	X
ASTM D 7171 - 05	Hydrogen Content by NMR (% mass)			13.8	
ASTM D 4809 - 09ae1	Net Heat of Combustion (MJ/kg)			42.9	
ASTM D 3241 - 11a	Thermal Stability Breakpoint				
	Tube Deposit Rating, Visual			2	
	Change in Pressure (mmHg)			0	
	Breakpoint (°C)			280	

Dispositions:
For information purposes only.
Coordinated with Gordon Walker (PTOT), phone: DSN 785-6208, COM 937-255-6208.

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AFPET LABORATORY REPORT
AFPA/PTPLA
2430 C Street
Building 70, Area B
Wright-Patterson AFB, OH 45433-7632

Lab Report No:2013LA42771001	Date Received:03/04/13 1023 hrs*	Date Sampled: **
Cust Sample No:9326	Date Reported:03/14/13 0857 hrs*	Protocol:FU-AVI-0036
JON: GENERAL FUND		

Sample Submitter:
AFRL/RZPF
1790 Loop Road N
Bldg 490
Wright-Patterson AFB, OH 45433

Approved By	Date
Amanda Rowton \\SIGNED\\	03/14/2013*

This report was electronically delivered to:
amanda.rowton@wpafb.af.mil, donald.minus@wpafb.af.mil, gordon.walker@wpafb.af.mil, janet.swartz@wpafb.af.mil, jennifer.engelman@wpafb.af.mil, linda.shafer@wpafb.af.mil, michael.thiede@wpafb.af.mil, rhonda.cook.ctr@wpafb.af.mil

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Appendix B -
Long-Duration, Switched Fuel Testing Protocol for the Advanced Reduced Scale Fuel System Simulator (ARSFSS)

Long Term Switched Fuel Testing Profile For the Advanced Reduced Scale Fuel System Simulator (ARSFSS)

Premise:

ARSFSS testing using the Generic Durability Test Cycle mission set is normally the way to run. However, since each individual run (a mission set of 65+ missions) involves the replacement of test hardware components, some data repeatability concerns may arise. This is particularly a problem when there are limited quantities of fuel and when fuel thermal stability behavior is erratic.

It is well known that as deposition forms in the burner feed arm (BFA), this deposition lowers the heat transfer rate to the bulk fuel from the BFA sidewall. This results in a temperature rise in the BFA sidewall for fixed heater outputs. In this manner, BFA wetted wall temperature rise is a direct indication of deposition occurring along the wall within the BFA.

For cases where there is a limited fuel quantity or where fuel behavior has been erratic in normal ARSFSS mission testing, a different style of ARSFSS testing profile has been developed. It involves a long duration run where baseline and test fuel is alternated periodically and the temperature rise in the BFA is monitored. In this operations scenario, the variability of changing hardware components (BFA tubes, FCOC tubes, Servo and Flow Divider valves, etc.) is eliminated allowing of the variances in deposition to be more completely attributable to fuel differences. The down side to this style of testing is that flow valve hysteresis and carbon deposition (in terms of μgrams/cm²) are no longer available as a part of the data set since both baseline and test program fuel have been used on the same hardware.

Three Possible Result Scenarios

There are three likely result scenarios that might be expected from this testing profile.

Scenario 1 (Figure B-1)

In this scenario, the additive/contaminant or fuel under study has no impact on fuel thermal stability and hence no impact on deposition. In this case, the results will likely show a steady increase in temperature rise (and hence, deposition) for the duration of the test regardless of which fuel is being run.

Scenario 2 (Figure B-2)

In this scenario, the fuel thermal stability is significantly affected in a negative way by the additive, contamination or fuel. In this case, the results will likely resemble that presented in the prior figure.

Scenario 3 (Figure B-3)

In this scenario, the fuel thermal stability is improved by the additive/contamination/fuel. In this case the likely results would look like a mirror image of the prior figure and the changes would likely be less pronounced due to the inherently good thermal stability of fuels that are produced to the appropriate spec.

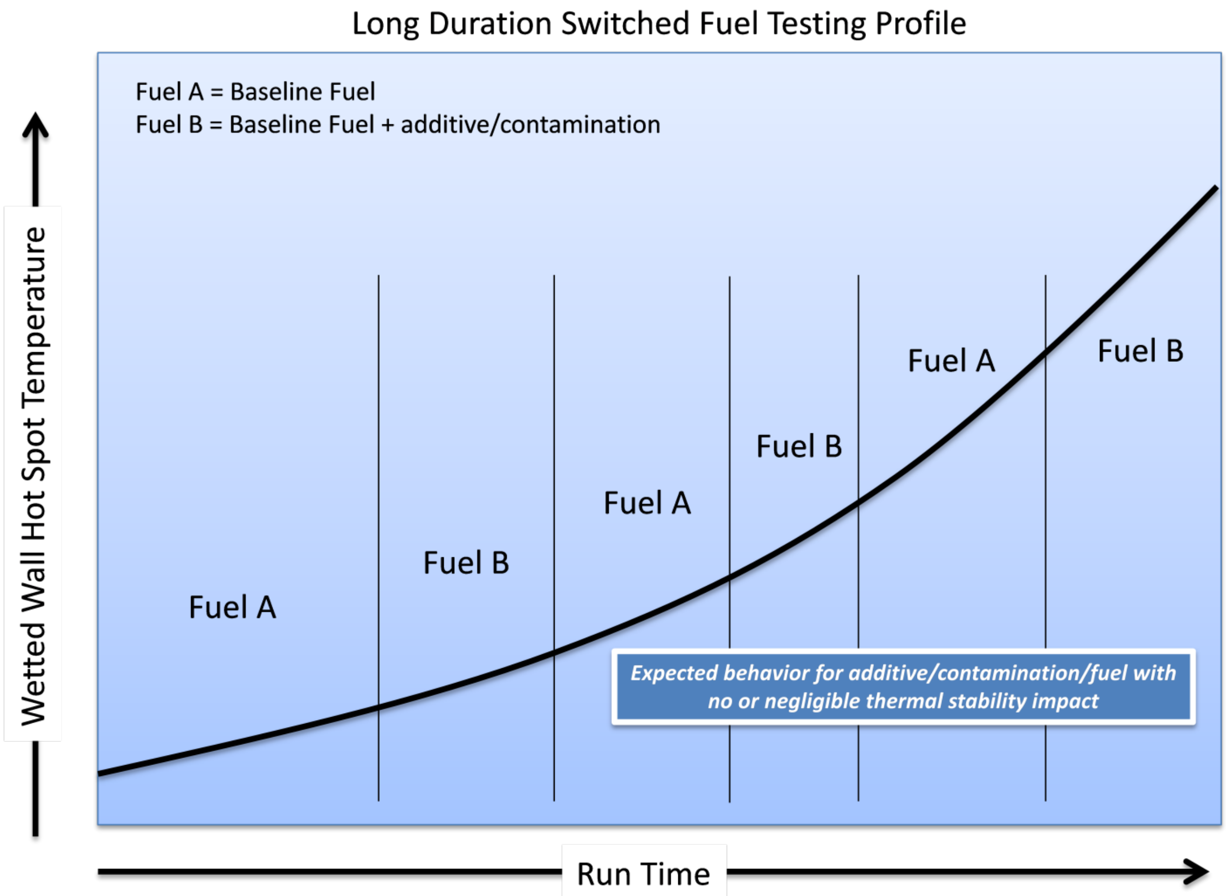

Long Duration Switched Fuel Testing Profile
Fuel A = Baseline Fuel
Fuel B = Baseline Fuel + additive/contamination
Wetted Wall Hot Spot Temperature
Fuel A
Fuel B
Fuel A
Fuel B
Fuel A
Fuel B
Expected behavior for additive/contamination/fuel with no or negligible thermal stability impact
Run Time

Figure B-1

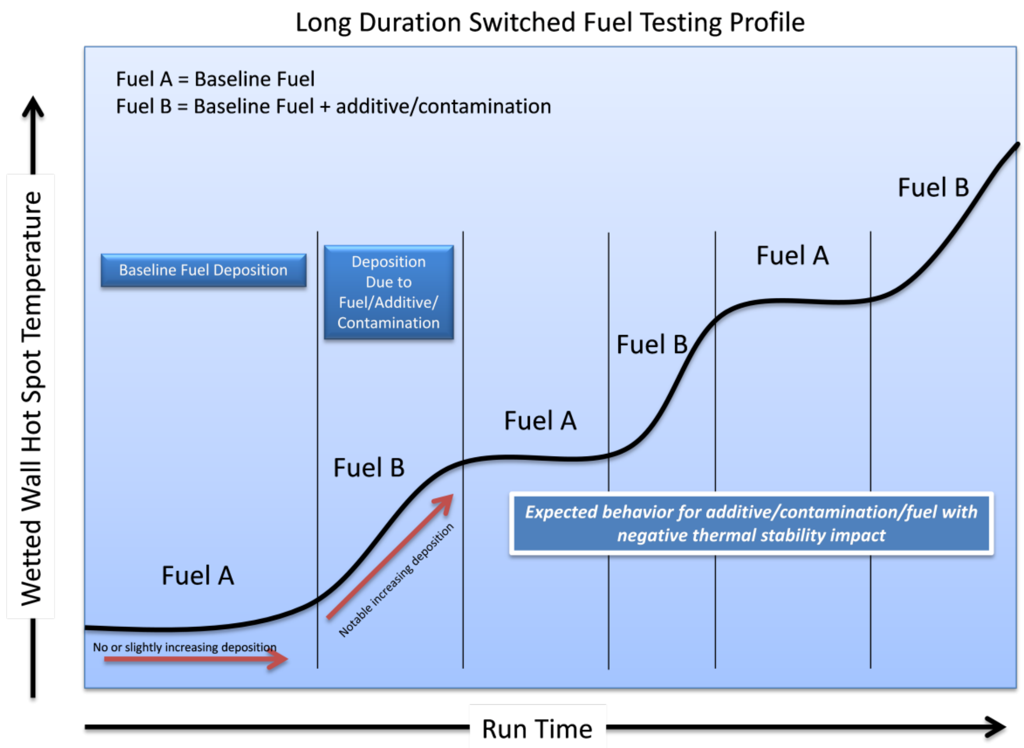


Figure B-2

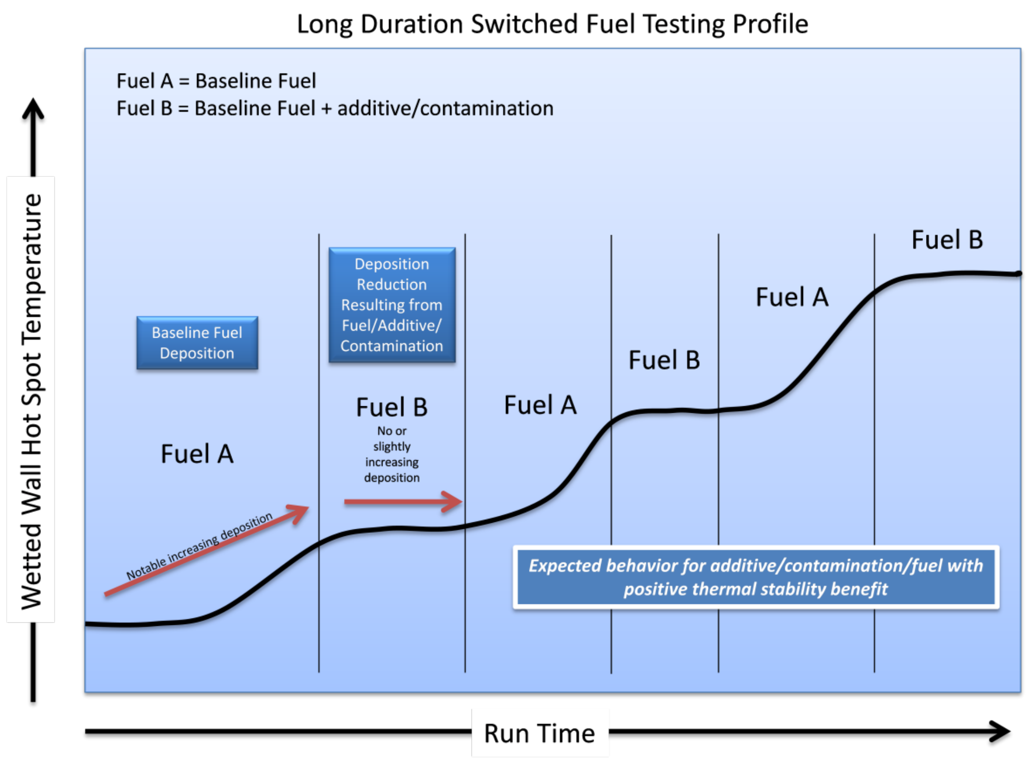


Figure B-3

Recommendation

This style of testing coupled with standard mission set testing may provide optimal evaluation of the fuel/additive/contaminant under study. In such coupled testing, 2-4 standard mission set runs would be executed to ‘bracket’ the behavior of the fuel/additive/contaminant under study. The appropriate run conditions would be selected to offer the greatest fidelity in the results.

This mode of combined testing also has the side benefit of performing testing under real-world conditions where the presence of the additive/contaminant/fuel is periodic.

Appendix C - Overall Data Summary Table

Table 8 – ARSFSS Runs and Tabulated Data Grouped by Fuel Type (light/dark colors) and Temperature Protocol

FAME CONTAMINATION TEST DATA SUMMARY

Run No.	Test Description	Missions[1] Or Hours	FAME PPM	MSN Type	FCOC Bulk Inlet °F	FCOC Bulk Fuel Outlet °F	BFA Max WWT °F	FCOC							BFA							AVG FDV Hyst, % [2]	AVG SRV Hyst, % [3]	NOTES
								Total Eff C µgrams	Max Deposition		Max WWT [4]		Max ΔT @ Hot Spot °F [4]	ΔT Rate @ Hot Spot °F/msn [4]	Total Eff C, µgrams	Max Deposition		Max WWT [4]		Max ΔT @ Hot Spot °F [4]	ΔT Rate @ Hot Spot °F/msn [4]			
									Segment #	µg/cm²	°F	°C				Segment #	µg/cm²	°F	°C			%	%	
92	Baseline Jet A	65	0	HT	325	375	500	588	3	11.17	391	199	0	0.000	1873	8	205.6	494	257	-7	-0.11	16	14.8	A,D
93	Baseline Jet A	65	0	MT	325	350	475	102	5	4.9	372	189	1	0.015	310	8	26.8	478	248	3	0.05	2.5	2.1	A
94	Baseline Jet A	65		LT	300	325	450	103	2	3	353	178	0	0.000	177	8	11.8	452	233	4	0.06	2.7	9.5	A
95	Baseline Jet A	65	0	HT	325	375	500	319	2	7.6	425	218	0	0.000	638	8	76	503	262	3	0.05	4	7.1	B
96	Jet A + FAME	65	400	HT	325	375	500	380	4	7.7	423	0	0	0.000	1037	8	105.6	504	262	4	0.06	2.8	11.2	C
97	Jet A + FAME	65	400	MT	325	350	475	99	3	1.9	375	191	0	0.000	185	8	18.3	475	246	1	0.02	-1.1	1	C
98	Jet A + FAME	65	400	LT	300	325	450	155	2	4.2	348	176	-1	-0.015	82	8	7	451	233	2	0.03	8.5	4.5	C
99	Jet A + FAME	65	400	HT	325	375	500	362	4	7.5	420	216	-1	-0.015	8757	8	1079	550	288	50	0.77	8.9	5.3	
100 *	Jet A + FAME	46	400	LT	300	325	450	231	4	4.6	346	174	-2	-0.043	1815	8	207	459	237	9	0.20	4.8	10.4	F
101	Jet A + FAME	65	400	LT	300	325	450	163	2	7.5	346	174	-1	-0.015	874	8	107	463	239	16	0.25	4.2	5.1	
102	Jet A + FAME	65	400	HT	325	375	500	858	4	35	423	217	1	0.015	66544	8	8532	602	317	102	1.57	14.1	29.2	D
103	Baseline Jet A	65	0	HT	325	375	500	429	4	16.7	421	216	1	0.015	1499	9	120.7	500	260	0	0.00	1.8	2.3	
104	Jet A + FAME	65	400	HT	325	375	500	455	4	16	429	221	1	0.015	882	8	90	500	260	1	0.02	8.3	1.4	
105	Jet A + FAME	204	400	HT	325	375	510	185	4	46.5	425	218	2	0.010	17300	8	4543	510	266	107	0.52	8.7	8.8	E
Tests below are EDTST Mode tests. Carbon and hysteresis data provided for comparison to like-mode tests only and are not directly comparible to the data obtained in GTDC mode (above)																								
90	Baseline Jet A	72 Hours	0	EDTST	325	375	510	270	2	10.2	NOT APPLICABLE				7083	8	942	NOT APPLICABLE				1.7	-0.4	F
91	Jet A + FAME	72 Hours	400	EDTST	325	375	510	83	4	8.9	NOT APPLICABLE				430	8	51.6	NOT APPLICABLE				1.3	1.7	F
106	Jet A + FAME	72 Hours	400	EDTST	325	375	510	117	4	5.8	NOT APPLICABLE				135	9	12.3	NOT APPLICABLE				2	5.7	F
107	Baseline Jet A	72 Hours	0	EDTST	325	375	510	72	5	4.9	NOT APPLICABLE				180	9	10.1	NOT APPLICABLE				1.4	2.3	F
108	Baseline Jet A	72 Hours	0	EDTST	325	375	510	29.3	2	5.7	NOT APPLICABLE				11041	8	1554	NOT APPLICABLE				1.4	7.3	F
109	Jet A + FAME	72 Hours	400	EDTST	325	375	510	101	5	3.4	NOT APPLICABLE				2317	8	299	NOT APPLICABLE				2.6	2.2	F
110	Jet A (10325)	72 Hours	0	EDTST	325	375	510	112	2	5.6	NOT APPLICABLE				790	8	116	NOT APPLICABLE				1.1	4.3	F
111	Jet A (10325+FAME)	72 Hours	400	EDTST	325	375	510	23.4	2	4.4	NOT APPLICABLE				740	8	89.5	NOT APPLICABLE				0.5	3.6	F

Notes:

1. Typically, 65 missions will be used based on the Generic Durability Test Cycle mission profile normally used for the ARSFSS. However, the number of missions may be increased as needed.

2. Effective Average Hysteresis over an operating range for FCV303 of 30-80%, DP ~ 140-210 PISD; (Value = Average Post-Test - Average Pre-Test)

3. Effective Average Hysteresis over an operating range for FCV701 of 40-65%, DP ~ 120-180 PISD; (Value = Average Post-Test - Average Pre-Test)

4. At HP Cruise Condition

** Aborted after 46 complete missions due to BFA WWT hot spot over temp (>600 °F)*

NOTE A: Testing at three temperature profiles representative of Legacy, Intermediate, and Advanced aircraft (military and commercial) to make sure the most effective temperature profile has been selected.

NOTE B: Re-run of Run 92 due to malfuntion in achieving heater steady state power output during the Run.

NOTE C: Testing at three temperature profiles using FAME-contaminated fuel. System flush and overnight soak in FAME-contaminated fuel.
This directly relates to the above baseline tests and will allow evaluation of potential FAME impact to Legacy, Intermediate and Advanced aircraft configurations (military and commercial). It will also allow for final selection of test conditions for additional testing as required.

NOTE D: Test terminated after 45 missions due to deposition in BFA causing BFA WWT to excede system safety limits

NOTE E: Combined FAME/Baseline run to determine behavior when transitioning from FAME to Baseline fuel. Test run until BFA temperature increase documented and then switch to Jet A Baseline to see if trend continues, stabilizes or reduces. This should indicate a true effect of FAME if any. Most of test run at 510 °F WWT BFA. Total Run 204 mission cycles.

NOTE F: EDTST Mode tests. Some data is not directly comparible to GDTC mission test data.

NOTE: The color scheme, as in the plots in the body of the report, are significant and represent an attempt to allow the reader to more easily assimilate the data and understand the results in terms of fuel (contaminated or baseline) and the three temperature regimes that the ARSFSS was operated over. The light colors indicate that these runs were performed using the baseline fuel with no FAME contamination. Dark colors indicate that the run was performed using the baseline fuel PLUS FAME contamination. The colors are also grouped by family. The reddish colors indicate the runs were performed using the High Temperature GDTC profile; the bluish colors indicate the runs were performed using the Low Temperature GDTC profile; greenish colors indicate the runs were performed using the Mid-Temperature GDTC profile. This hopefully allows a quick, more visual organization to the data.

Table 9 – Run Log Showing Start and Ending Dates for Each Run

Run Log			
Run No.	**Run Dates**		**Notes**
90	25-Mar-13	28-Mar-13	EDTST Protocol, 72 hours
91	2-Apr-13	5-Apr-13	EDTST Protocol, 72 hours
92	26-Sep-12	2-Oct-12	
93	3-Oct-12	9-Oct-12	
94	10-Oct-12	16-Oct-12	
95	24-Oct-12	30-Oct-12	
96	1-Nov-12	10-Nov-12	
97	29-Nov-12	5-Dec-12	
98	15-Nov-12	21-Nov-12	
99	10-Jan-13	16-Jan-13	
100	17-Jan-13	21-Jan-13	45 Missions (system overtemp)
101	24-Jan-13	30-Jan-13	
102	31-Jan-13	7-Feb-13	
103	13-Feb-13	19-Feb-13	
104	21-Feb-13	27-Feb-13	
105	28-Feb-13	18-Mar-13	LDSF Protocol, 204 Missions
106	29-Apr-13	2-May-13	EDTST Protocol, 72 hours
107	6-May-13	9-May-13	EDTST Protocol, 72 hours
108	8-Aug-13	8-Aug-13	EDTST Protocol, 72 hours
109	19-Aug-13	22-Aug-13	EDTST Protocol, 72 hours
110	26-Aug-13	29-Aug-13	EDTST Protocol, 72 hours
111	3-Sep-13	6-Sep-13	EDTST Protocol, 72 hours

Unless otherwise note, all runs used Generic Durability Test Cycle protocol at 65 missions

Appendix D - Servo Valve Hysteresis

Valve hysteresis can be defined as "The tendency of the position of a component to be dependent on the previous position of the component when reacting to a physical stimulus. Hysteresis leads to varying degrees of inaccuracy relative to valve actuation and target pressure." (*http://www.toolingu.com/definition-570235-28481-hysteresis.html*).

For the ARSFSS, hysteresis is the tendency for the valve to allow different flow values depending on whether the previous position of the valve was in a flow increasing or flow decreasing mode.

Variance in flow through a valve due to this hysteresis can adversely affect controls and propulsion-related fuel flows, hence it is desired to keep valve hysteresis to a minimum.

Average of Sets 1 and 2: in the following plots, hysteresis measurements are made by operating the valve at fixed delta-Ps to obtain flow values. These measurements are made in two directions (flow increasing and flow decreasing). Because the initial making of these measurements can result in the valve breaking free which will change any following hysteresis measurements, hysteresis measurements are made twice. The average of these two measurements is considered to be the best representation of actual valve hysteresis.

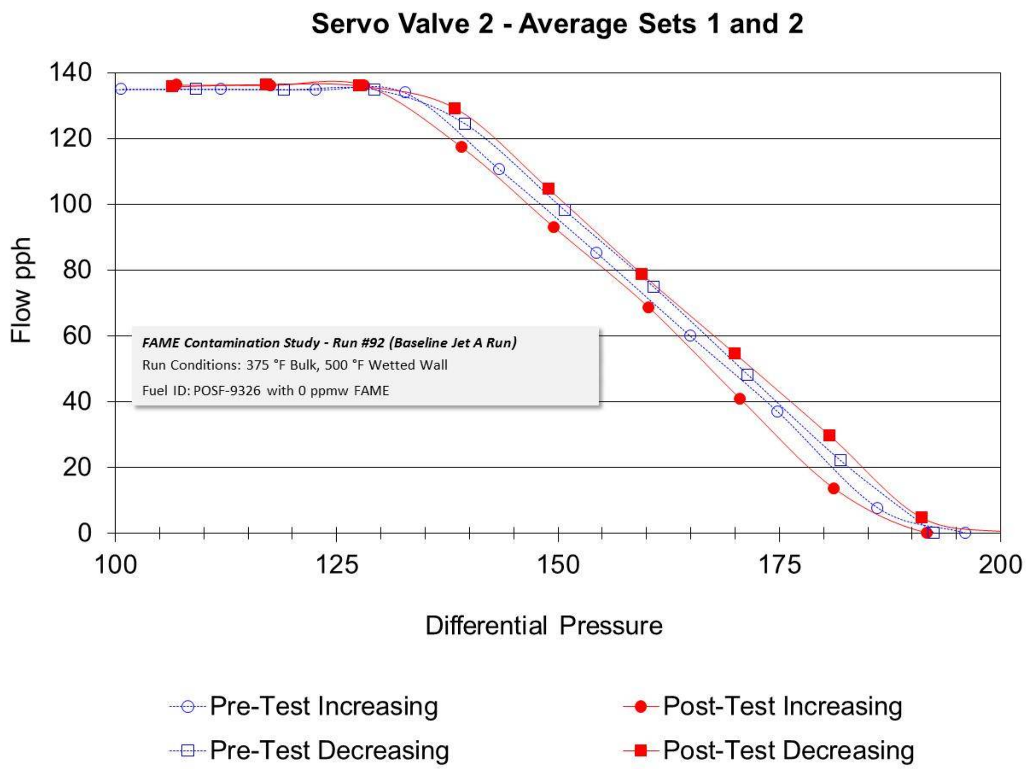


Figure D- 1 Servo Valve Hysteresis, Run 92, Baseline, HT Temperature Profile

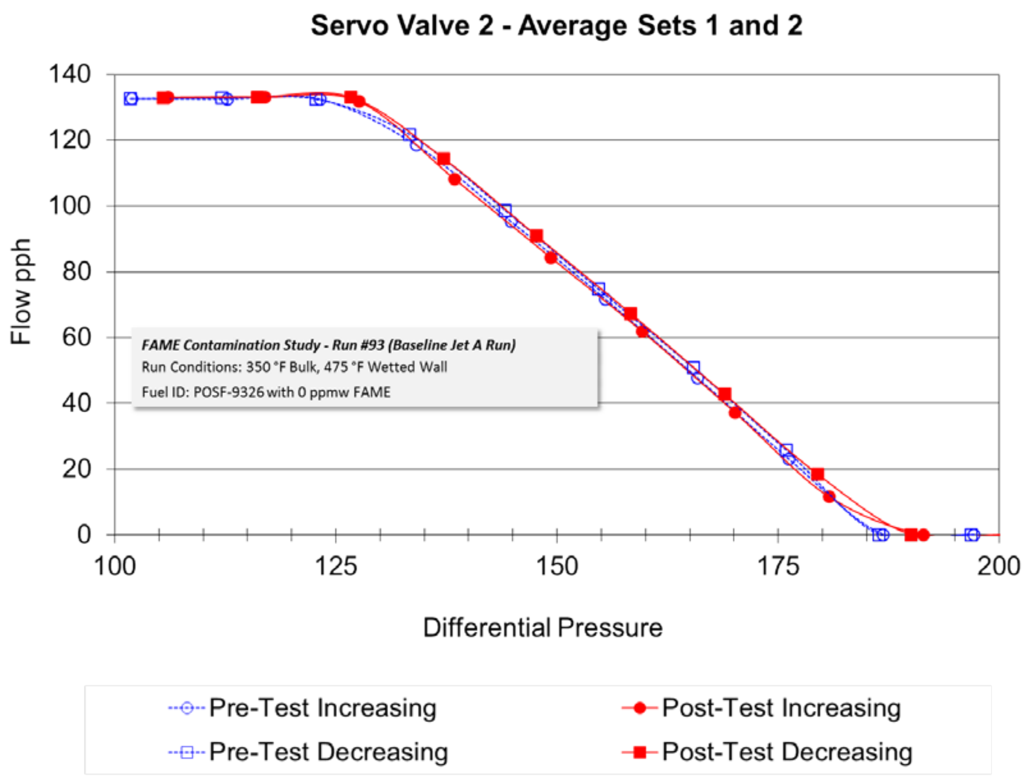


Figure D- 2 Servo Valve Hysteresis, Run 93, Baseline, MT Temperature Profile

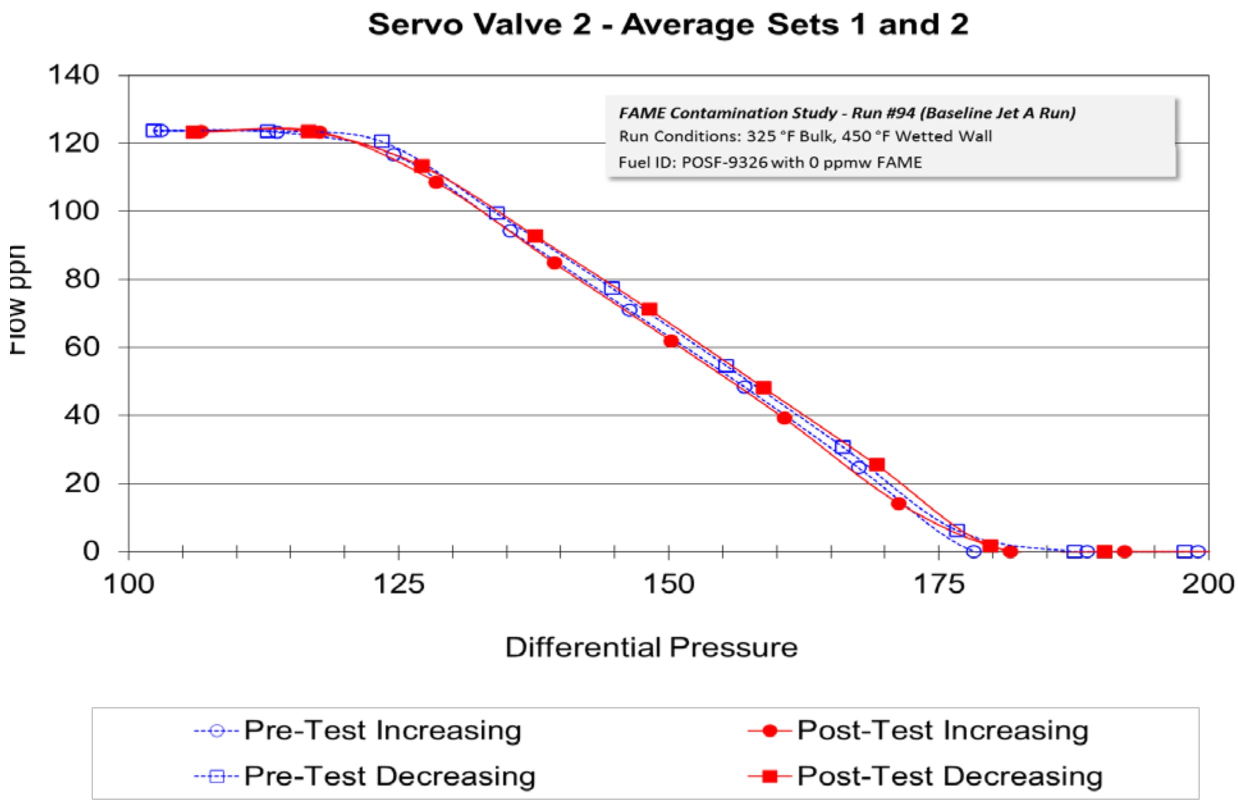


Figure D- 3 Servo Valve Hysteresis, Run 94, Baseline, LT Temperature Profile

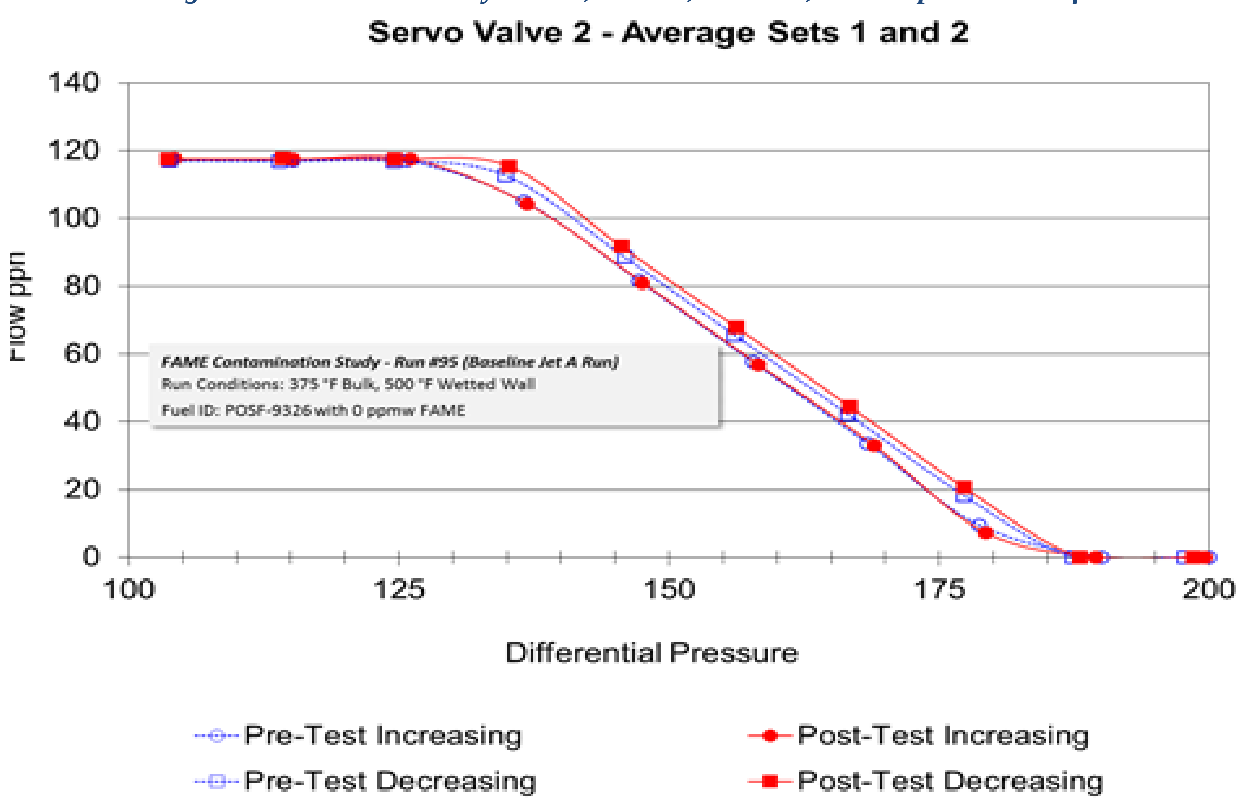


Figure D- 4 Servo Valve Hysteresis, Run 95, Baseline, HT Temperature Profile (Repeat of Run 92)

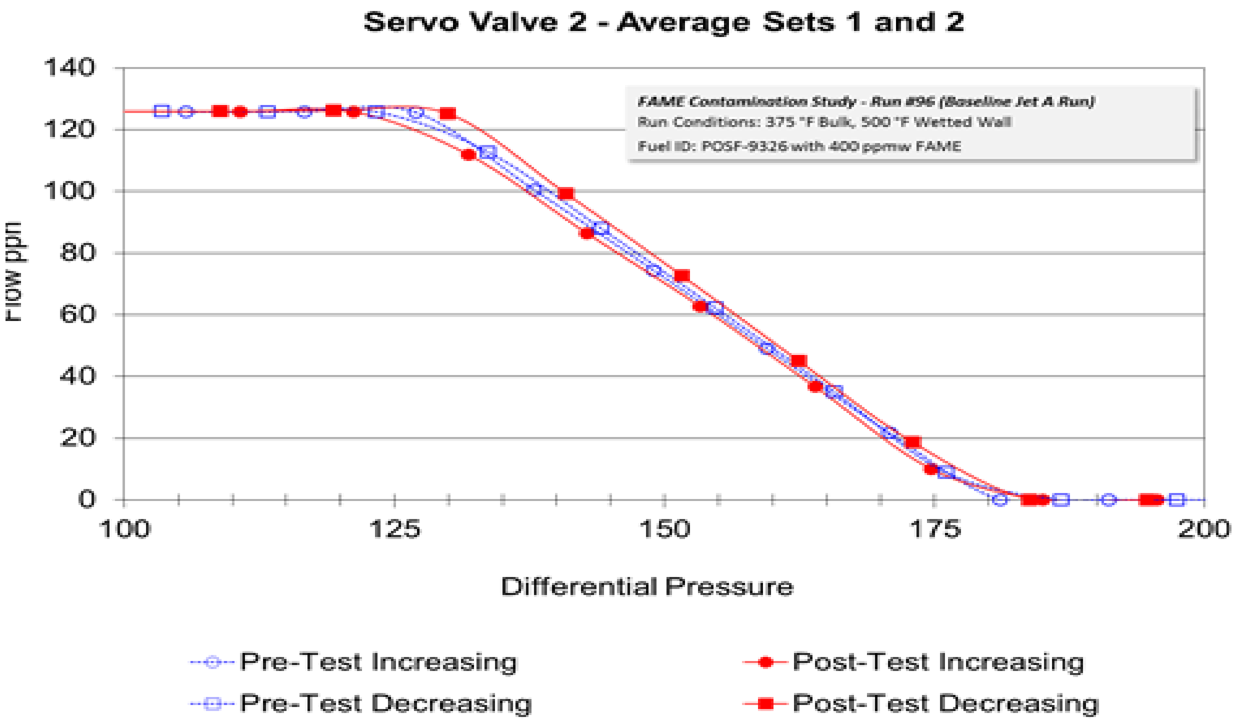


Figure D- 5 Servo Valve Hysteresis, Run 96, 400 PPM FAME, HT Temperature Profile

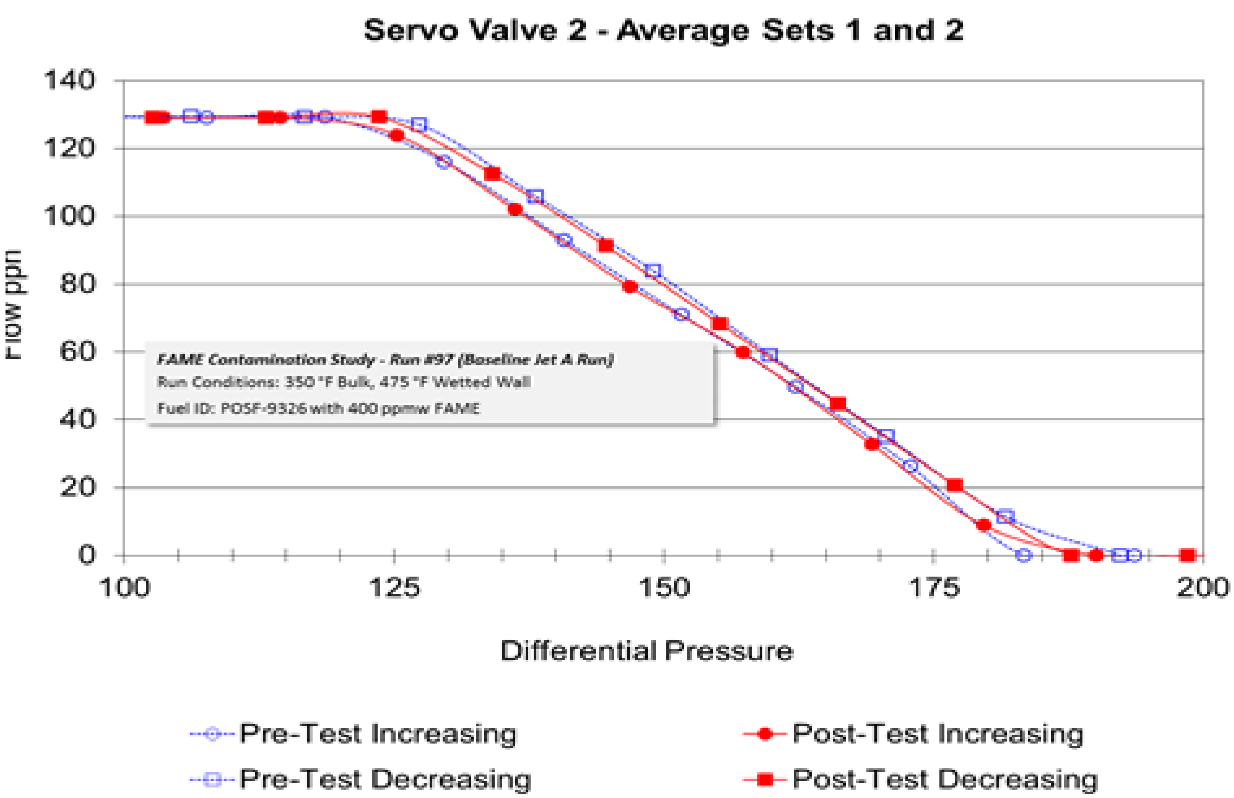


Figure D- 6 Servo Valve Hysteresis, Run 97, 400 ppm FAME, MT Temperature Profile

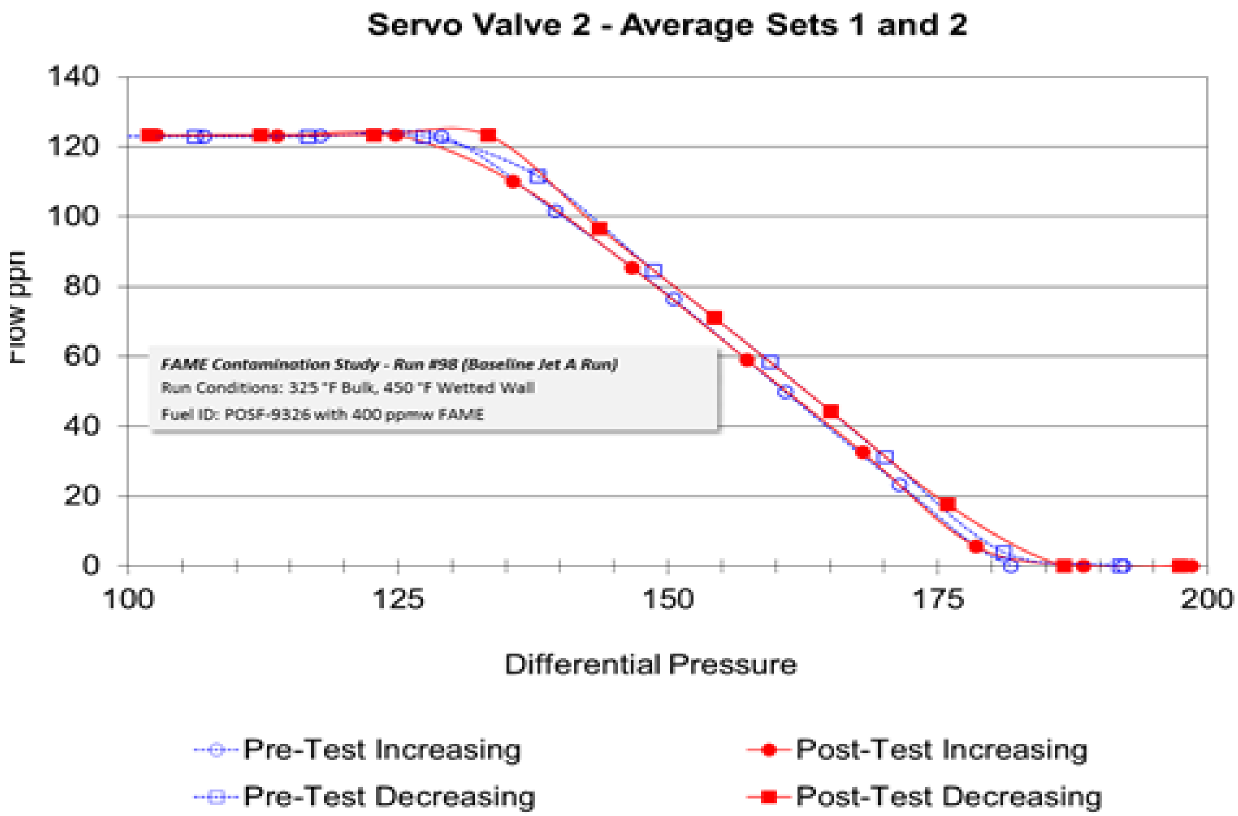


Figure D- 7 Servo Valve Hysteresis, Run 98, 400 PPM FAME, LT Temperature Profile

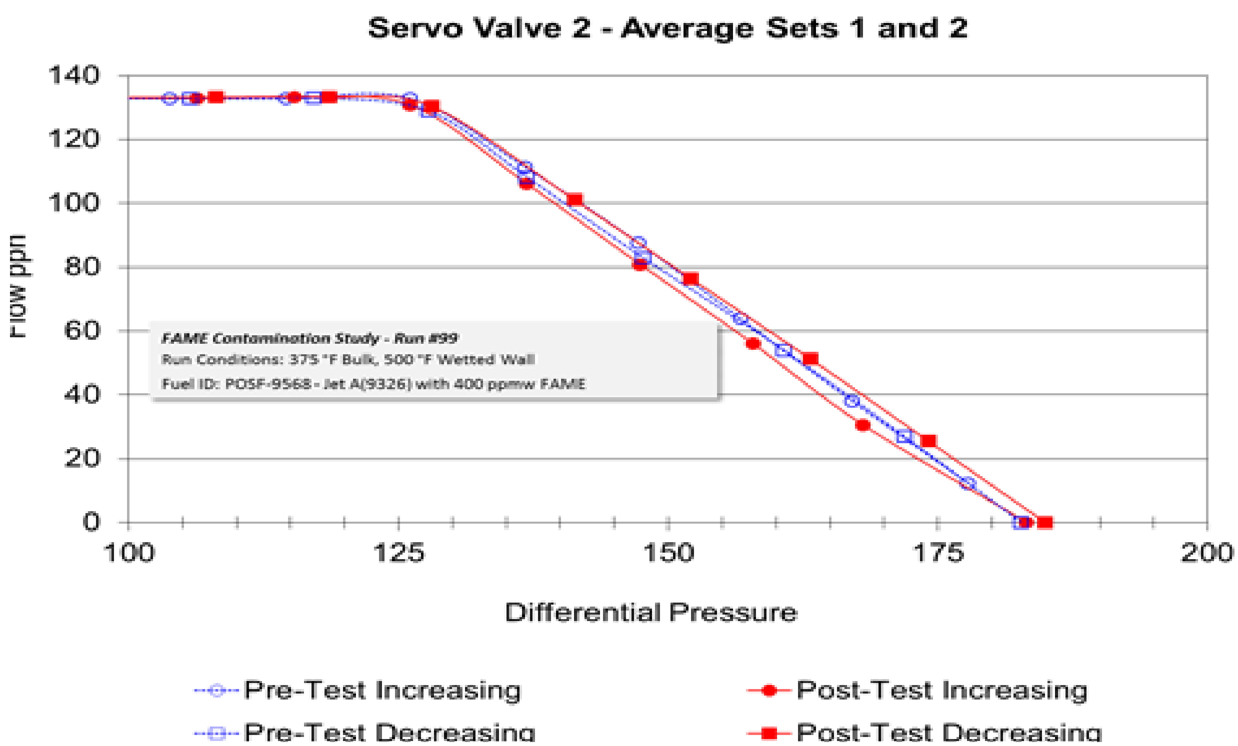


Figure D- 8 Servo Valve Hysteresis, Run 99, 400 PPM FAME, HT Temperature Profile

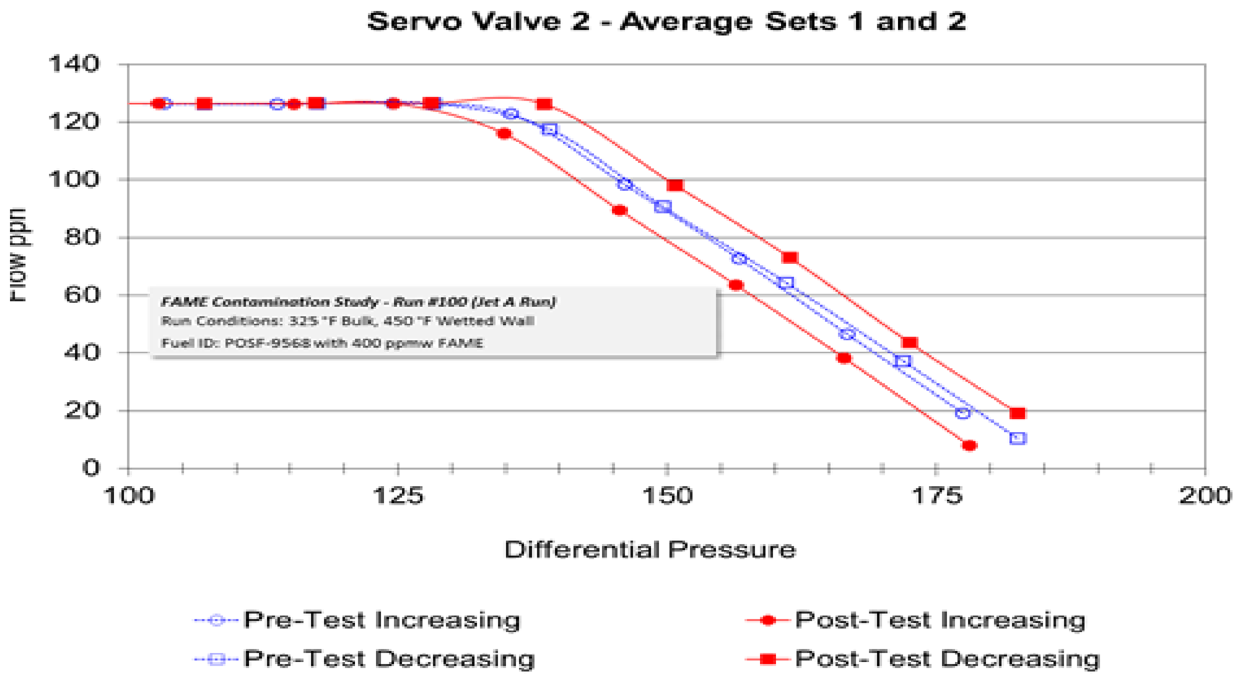


Figure D- 9 Servo Valve Hysteresis, Run 100, 400 PPM FAME, LT Temperature Profile

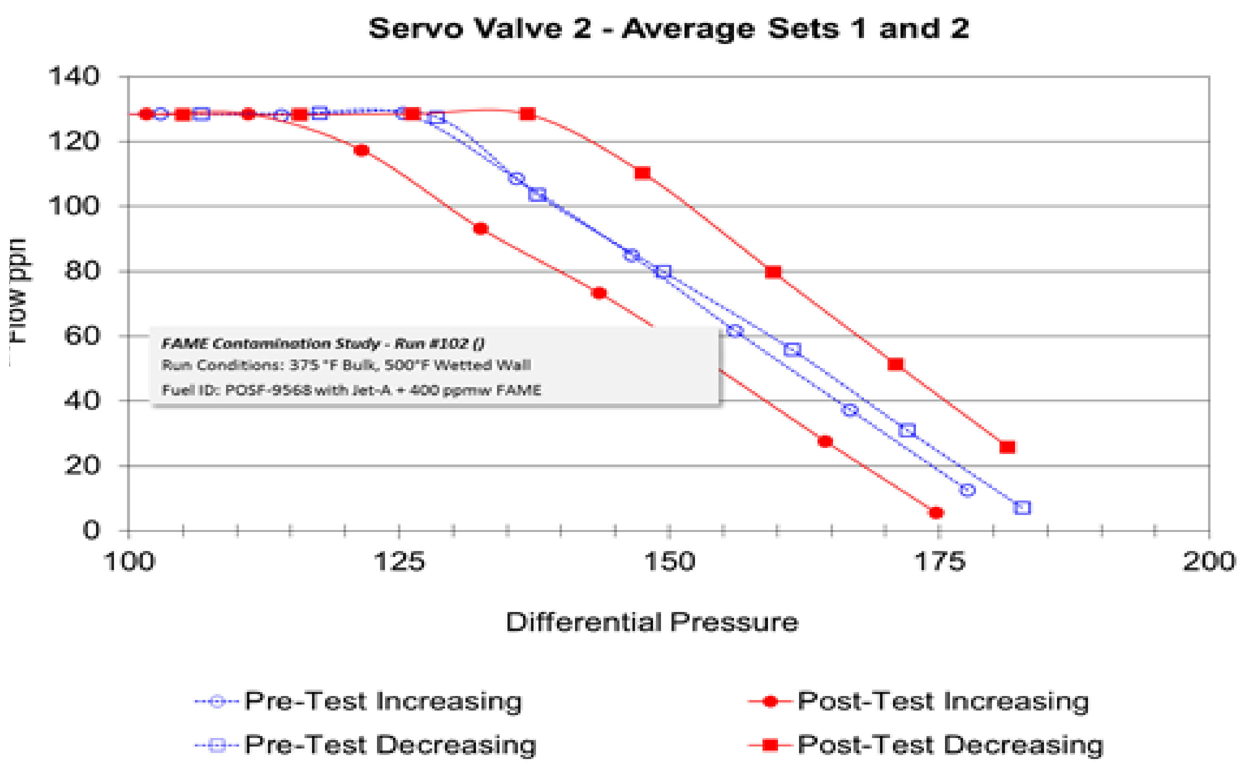


Figure D- 10 Servo Valve Hysteresis, Run 101, 400 PPM FAME, LT Temperature Profile

Figure D- 11 Servo Valve Hysteresis, Run 102, 400 PPM FAME, HT Temperature Profile

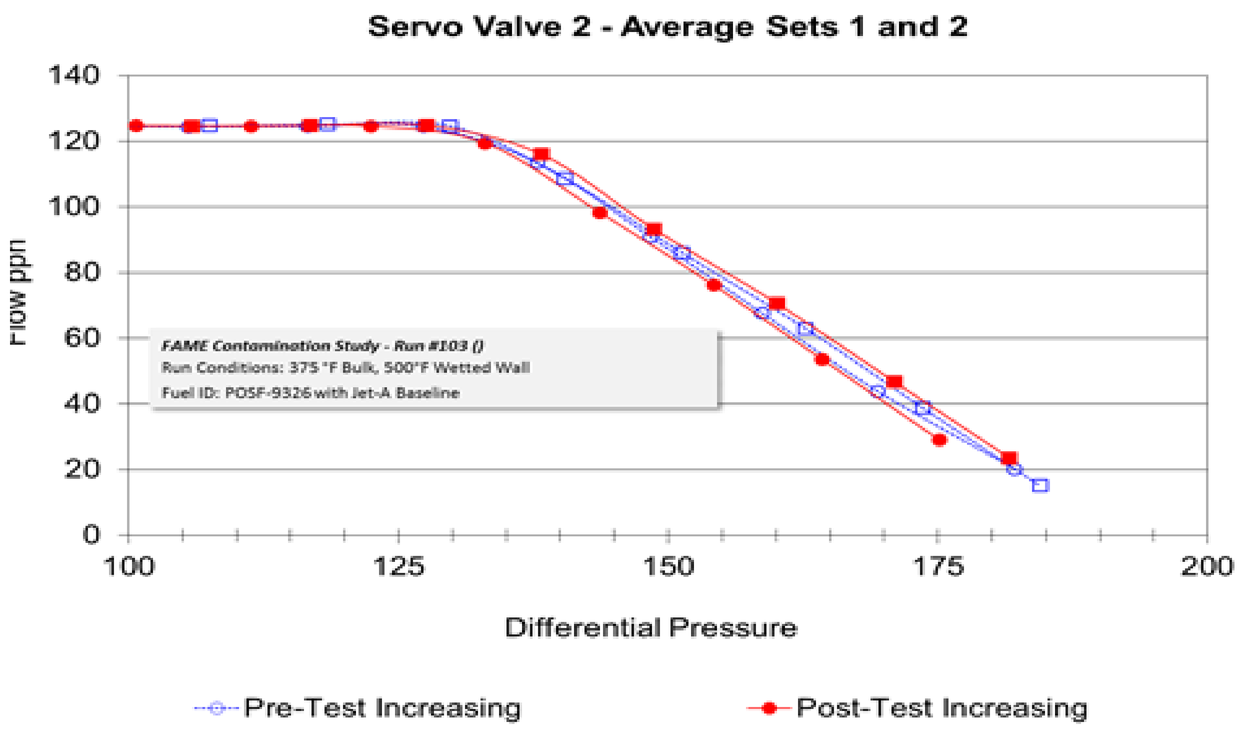


Figure D- 12 Servo Valve Hysteresis, Run 103, Baseline Jet A, HT Temperature Profile

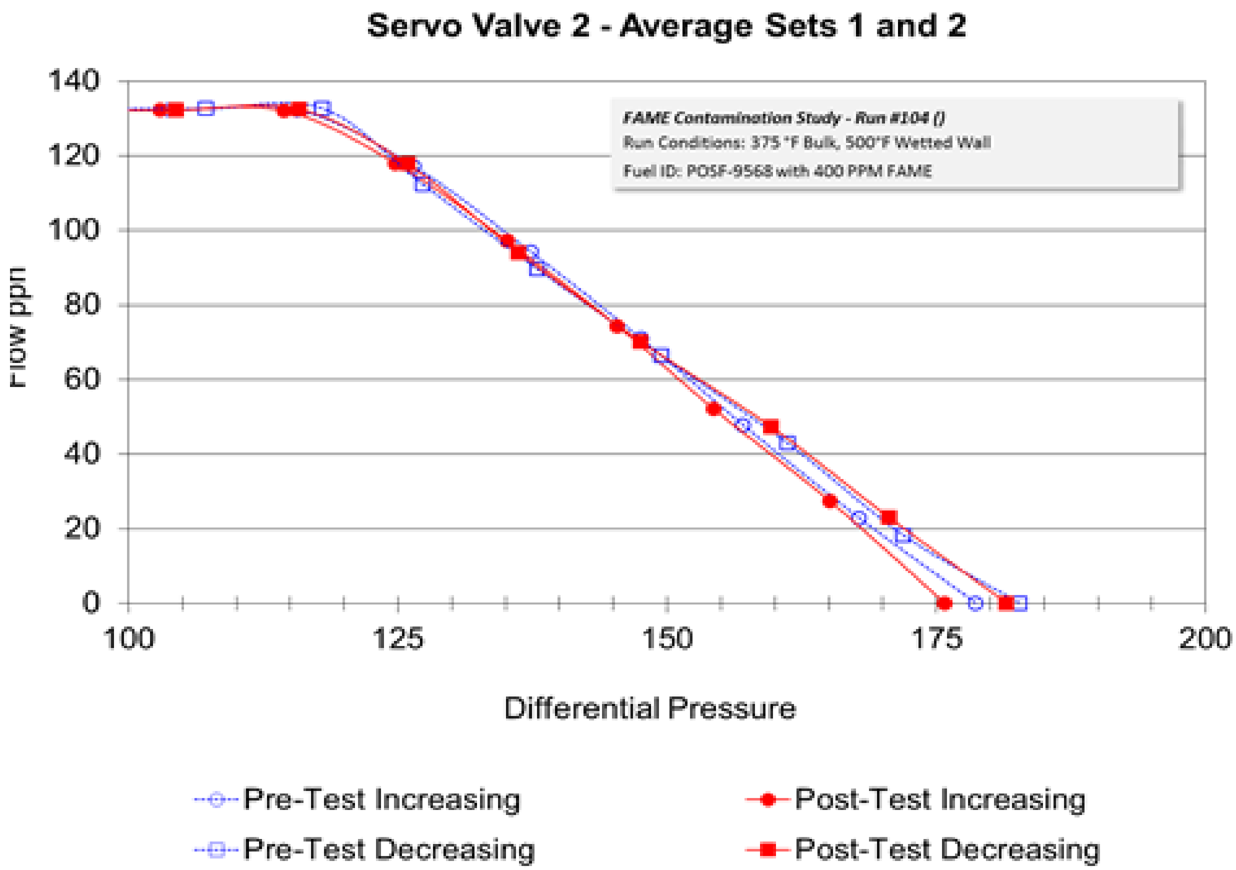


Figure D- 13 Servo Valve Hysteresis, Run 104, 400 PPM FAME, HT Temperature Profile

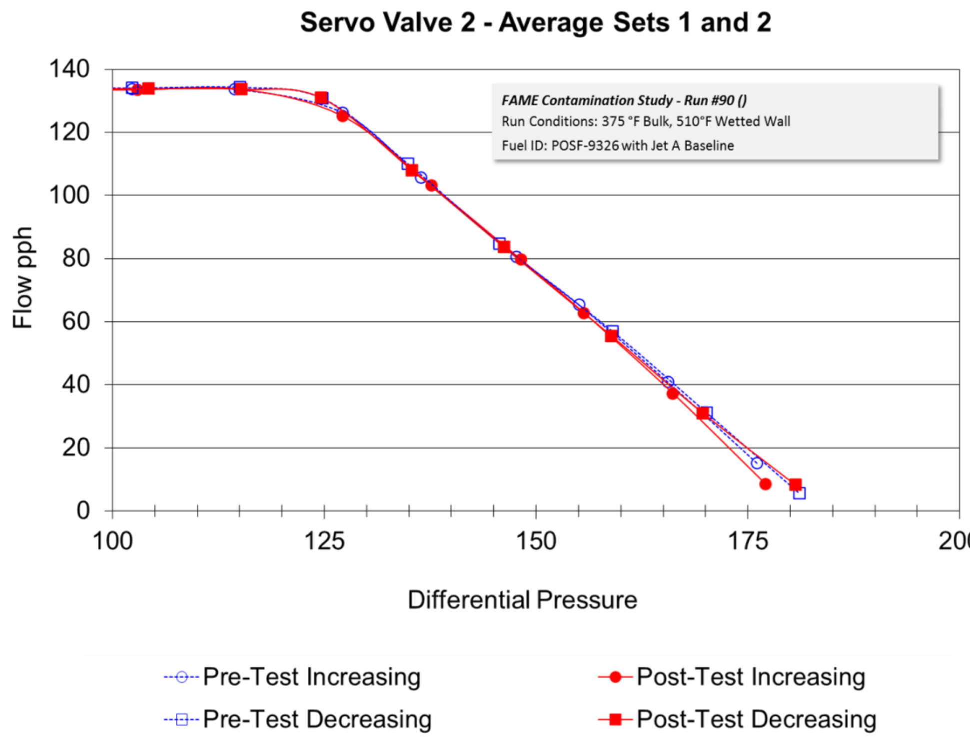


Figure D- 14 Servo Valve Hysteresis, Run 90, Baseline, HT+ Temperature Profile, EDTST Protocol

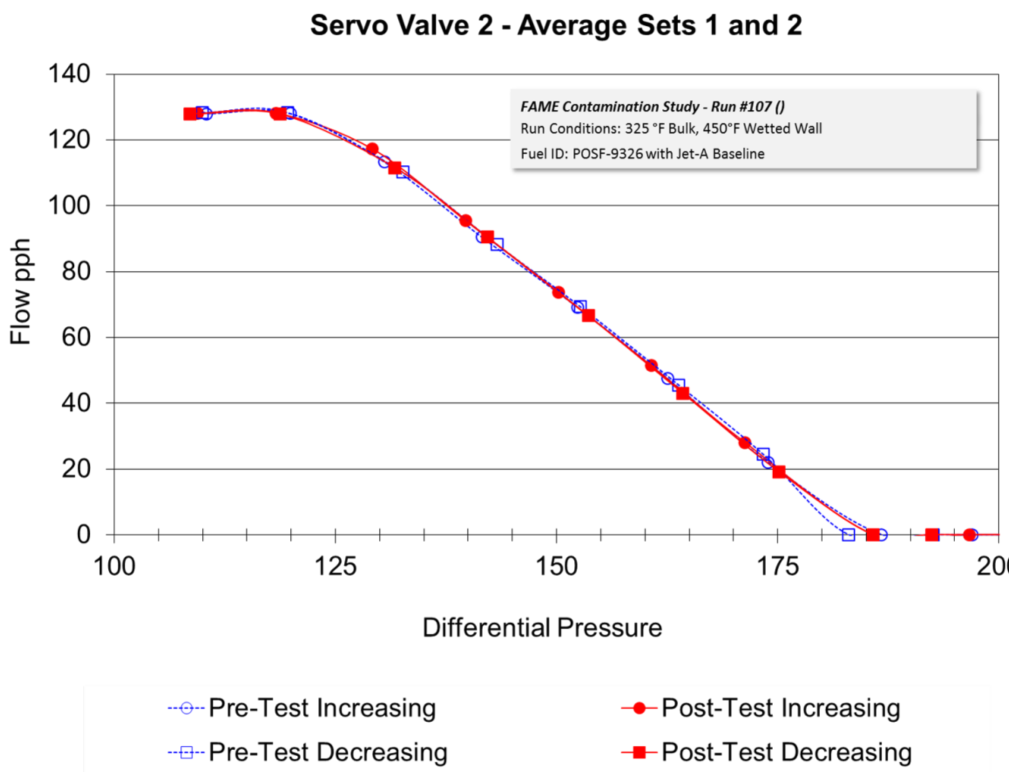


Figure D- 15 Servo Valve Hysteresis, Run 107, Baseline, HT+ Temperature Profile, EDTST Protocol

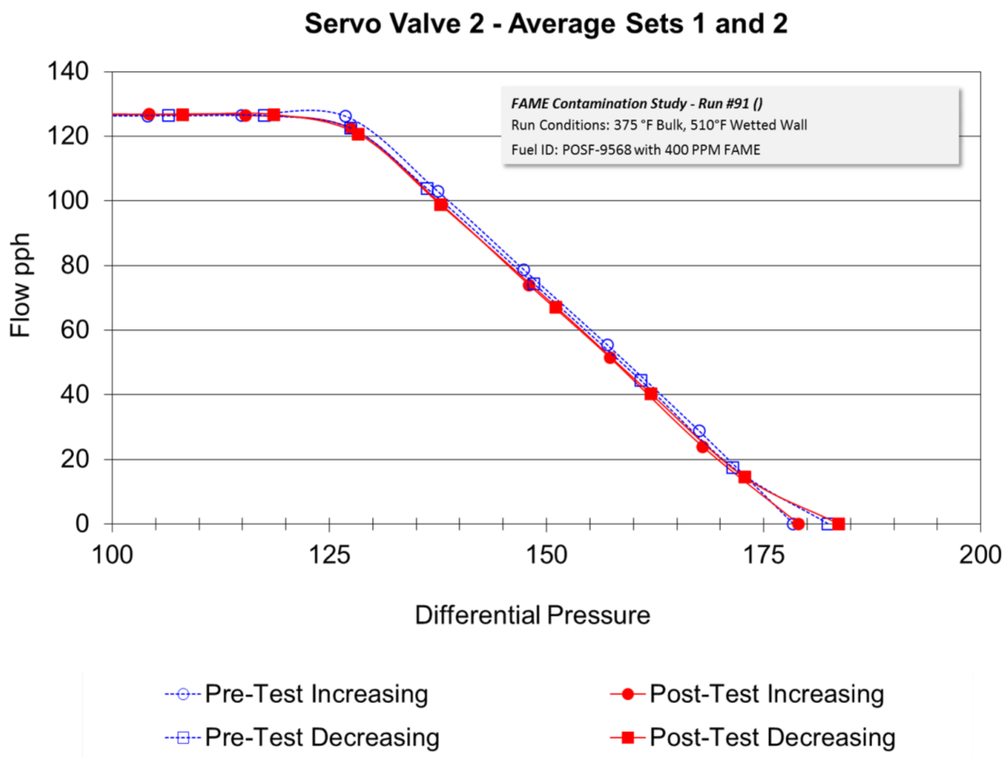


Figure D- 16 Servo Valve Hysteresis, Run 91, FAME, HT+ Temperature Profile, EDTST Protocol

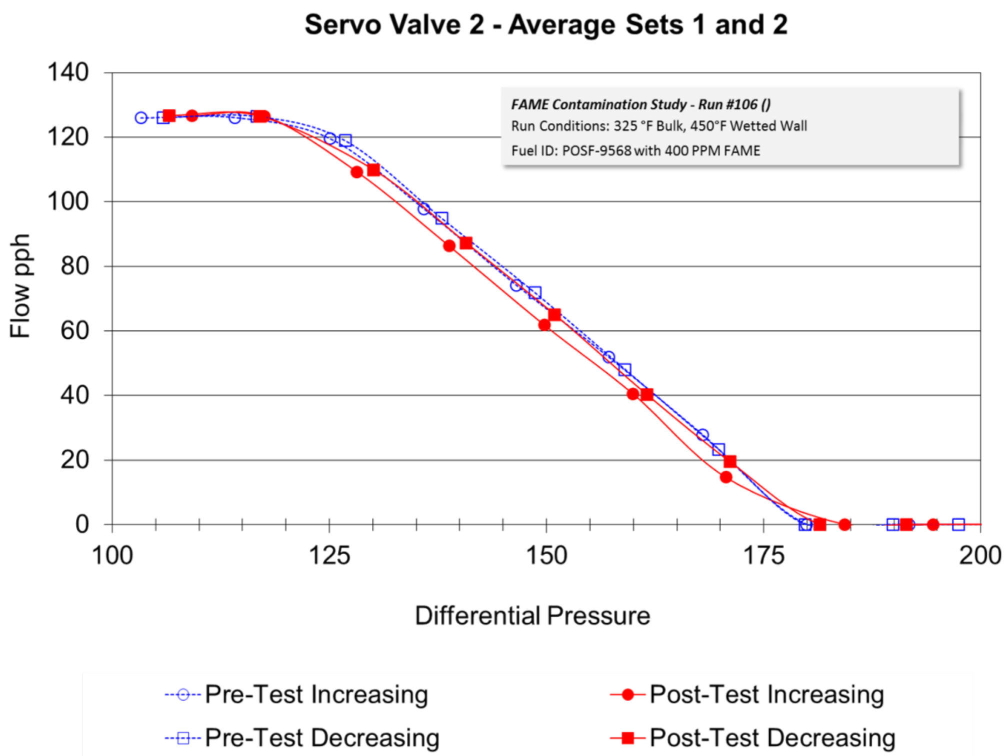


Figure D- 17 Servo Valve Hysteresis, Run 106, FAME, HT+ Temperature Profile, EDTST Protocol

Appendix E - Flow Divider Valve Hysteresis

Valve Hysteresis can be defined as "The tendency of the position of a component to be dependent on the previous position of the component when reacting to a physical stimulus. Hysteresis leads to varying degrees of inaccuracy relative to valve actuation and target pressure." (*http://www.toolingu.com/definition-570235-28481-hysteresis.html*).

For the ARSFSS, hysteresis is the tendency for the valve to allow different flow values depending on whether the previous position of the valve was in a 'flow increasing' or 'flow decreasing' mode.

Variance in flow through a valve due to this hysteresis can adversely affect controls and propulsion-related fuel flows, hence it is desired to keep valve hysteresis to a minimum.

Average of Sets 1 and 2: in the following plots, hysteresis measurements are made by operating the valve at fixed delta-Ps to obtain flow values. These measurements are made in two directions (flow increasing and flow decreasing). Because the initial making of these measurements can result in the valve 'breaking free' which will change any following hysteresis measurements, hysteresis measurements are made twice. The average of these two measurements is considered to be the best representation of actual valve hysteresis.

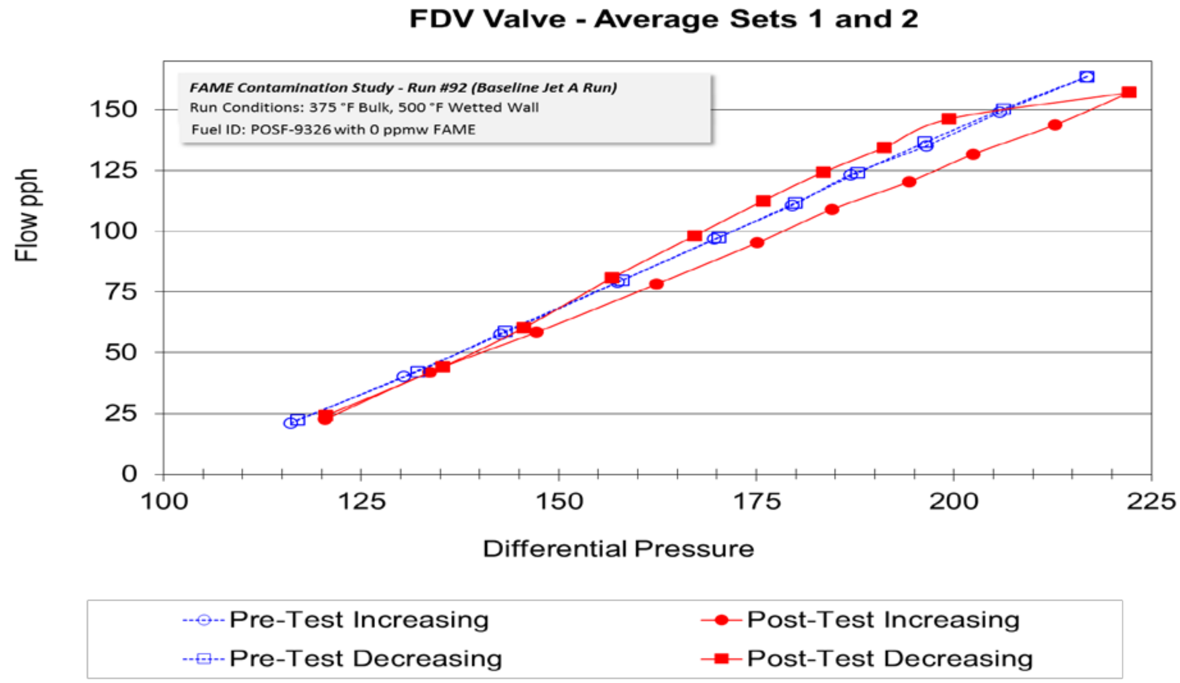


Figure E- 1 FDV Hysteresis, Run 92, Baseline Jet A, HT Temperature Profile

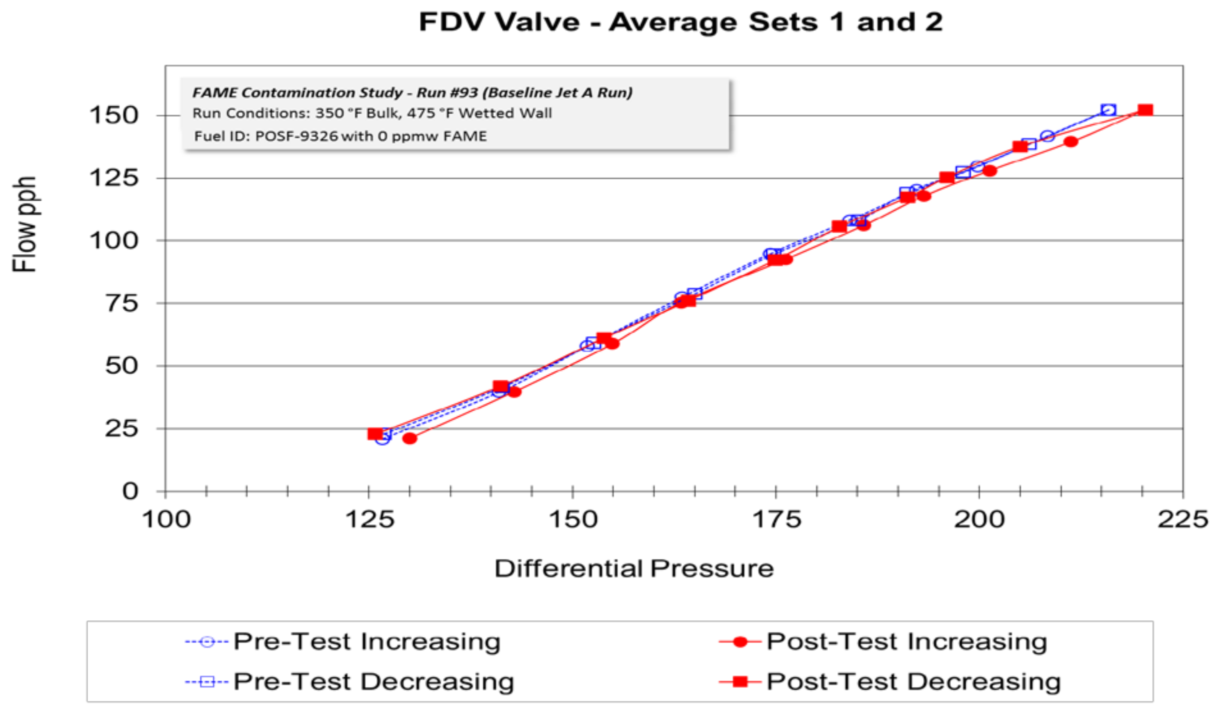


Figure E- 2 FDV Hysteresis, Run 93, Baseline Jet A, MT Temperature Profile

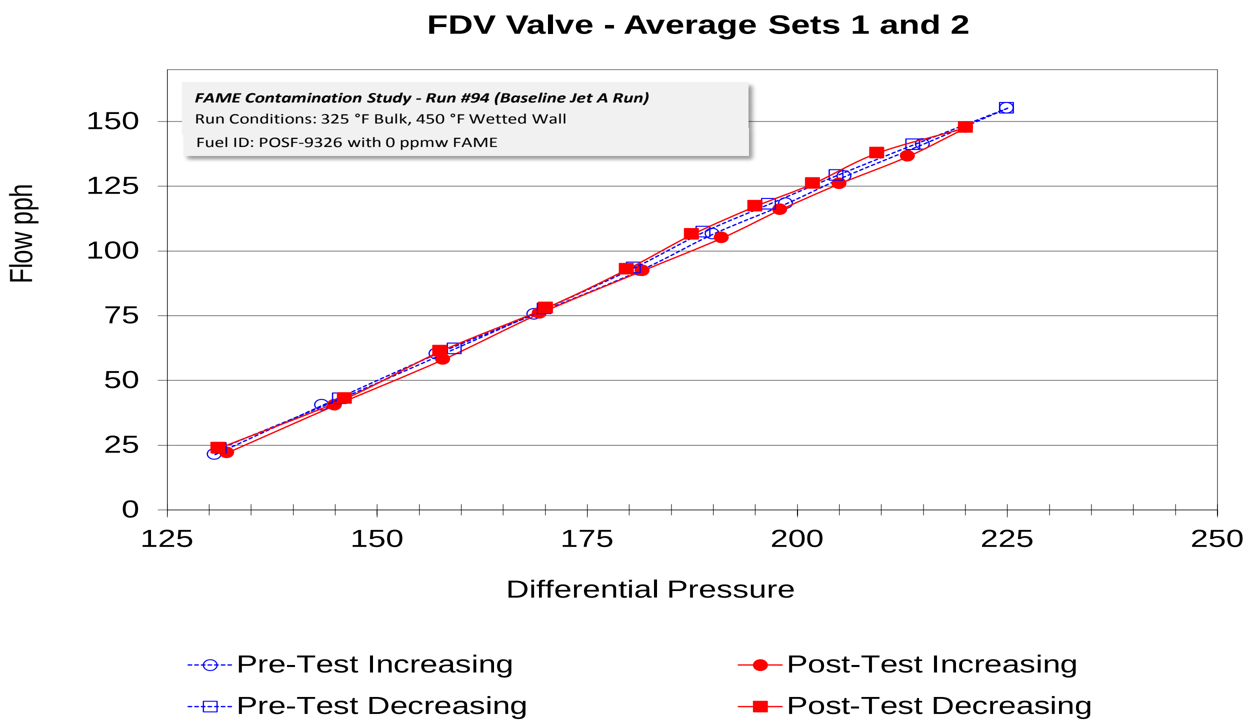


Figure E- 3 FDV Hysteresis, Run 94, Baseline Jet A, LT Temperature Profile

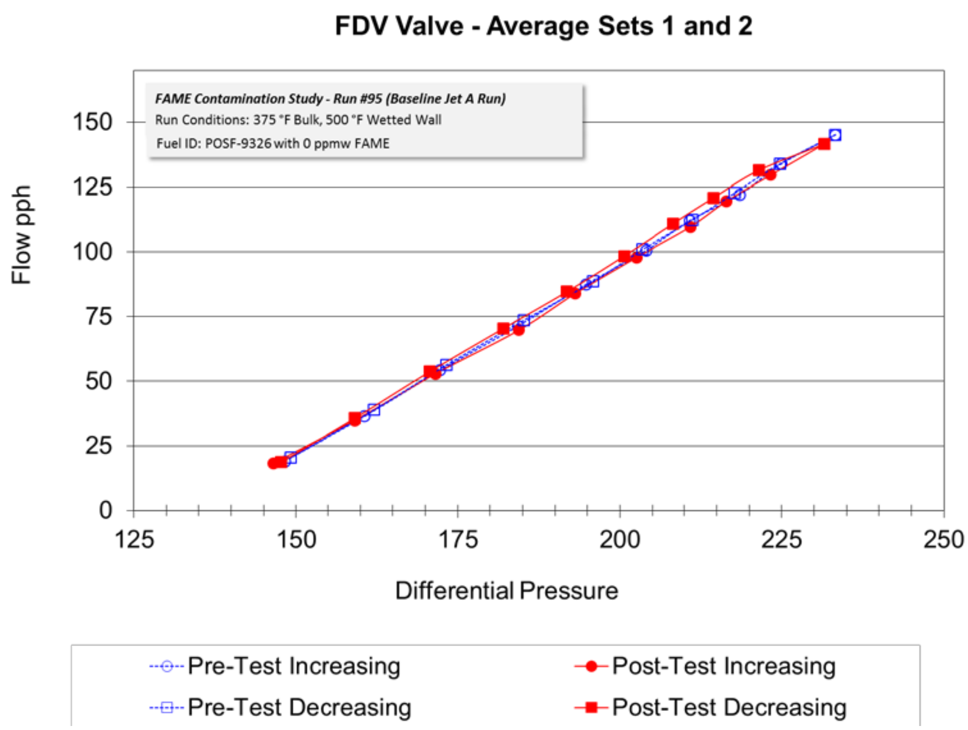


Figure E- 4 FDV Hysteresis, Run 95, Baseline Jet A, LT Temperature Profile (Rerun of Run 92)

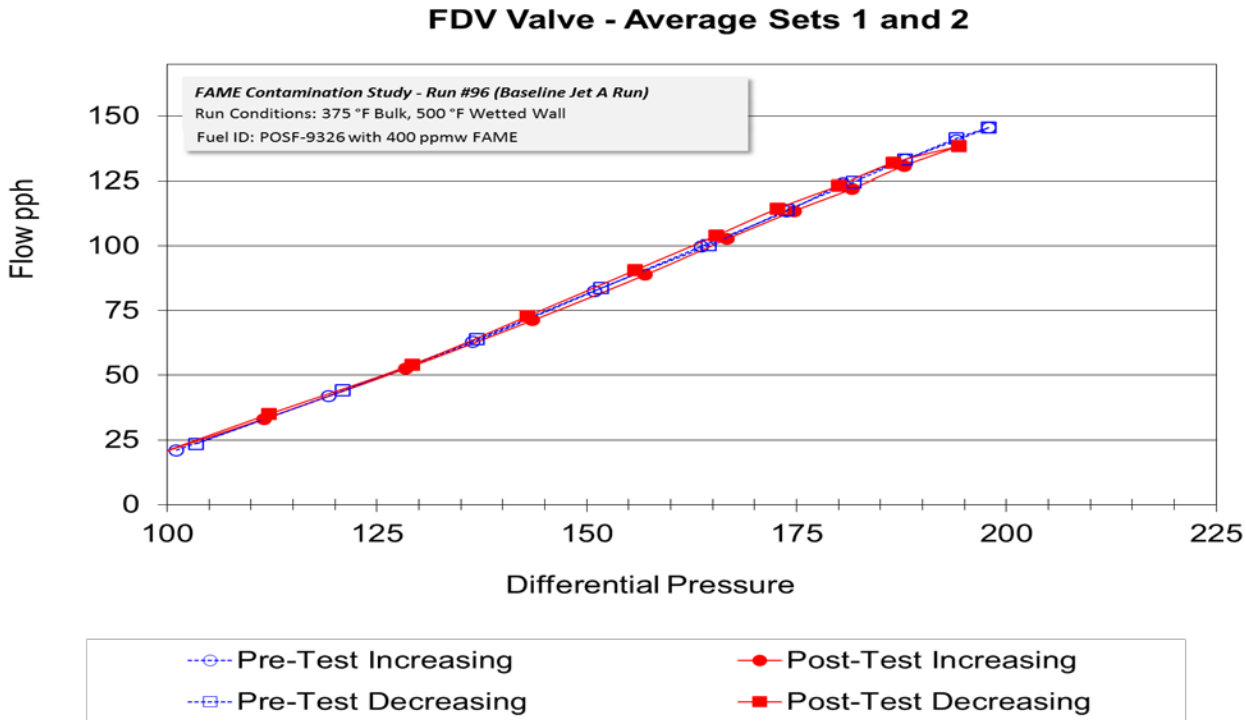


Figure E- 5 FDV Hysteresis, Run 96, 400 ppm FAME, HT Temperature Profile

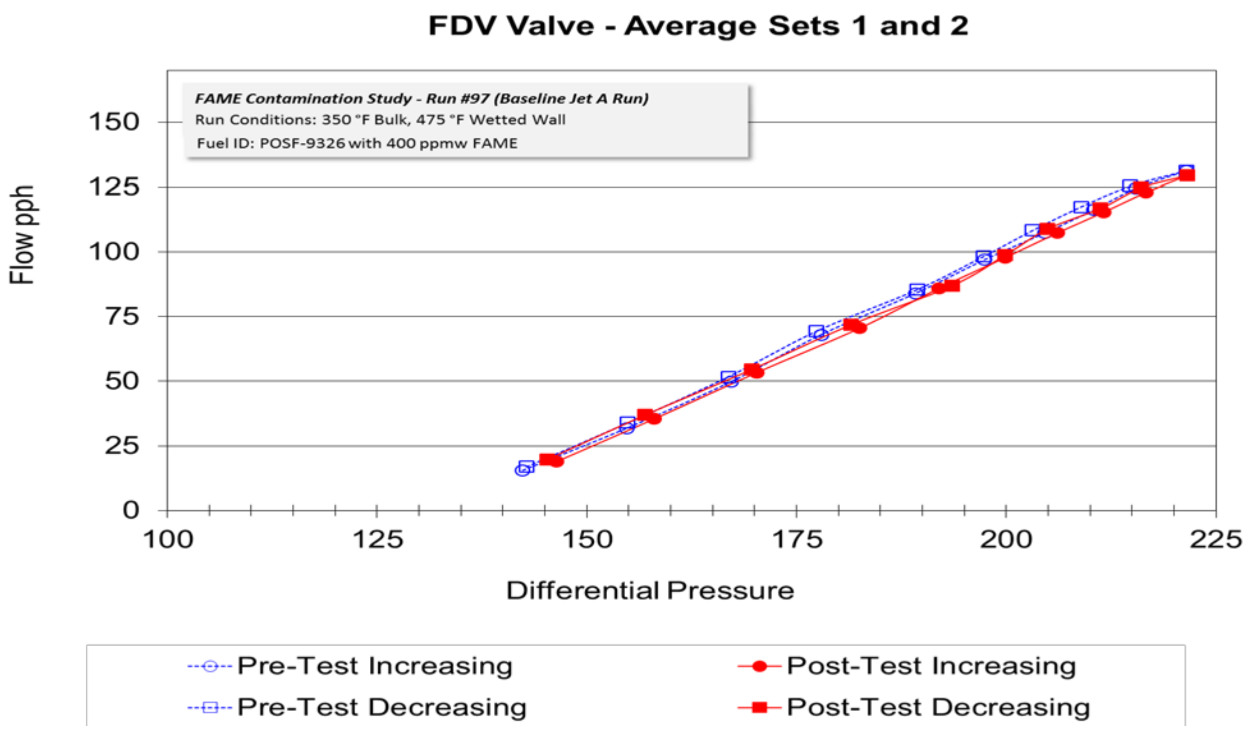


Figure E- 6 FDV Hysteresis, Run 97, 400 ppm FAME, MT Temperature Profile

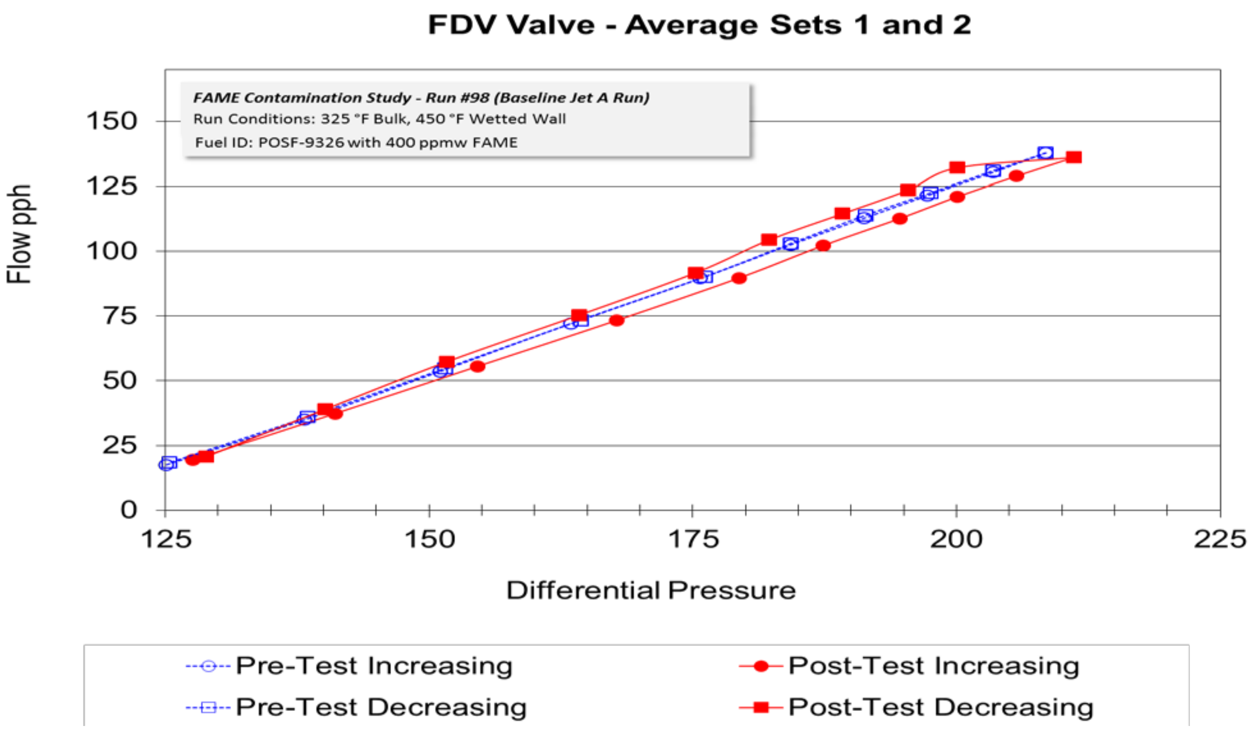


Figure E- 7 FDV Hysteresis, Run 98, 400 ppm FAME, LT Temperature Profile

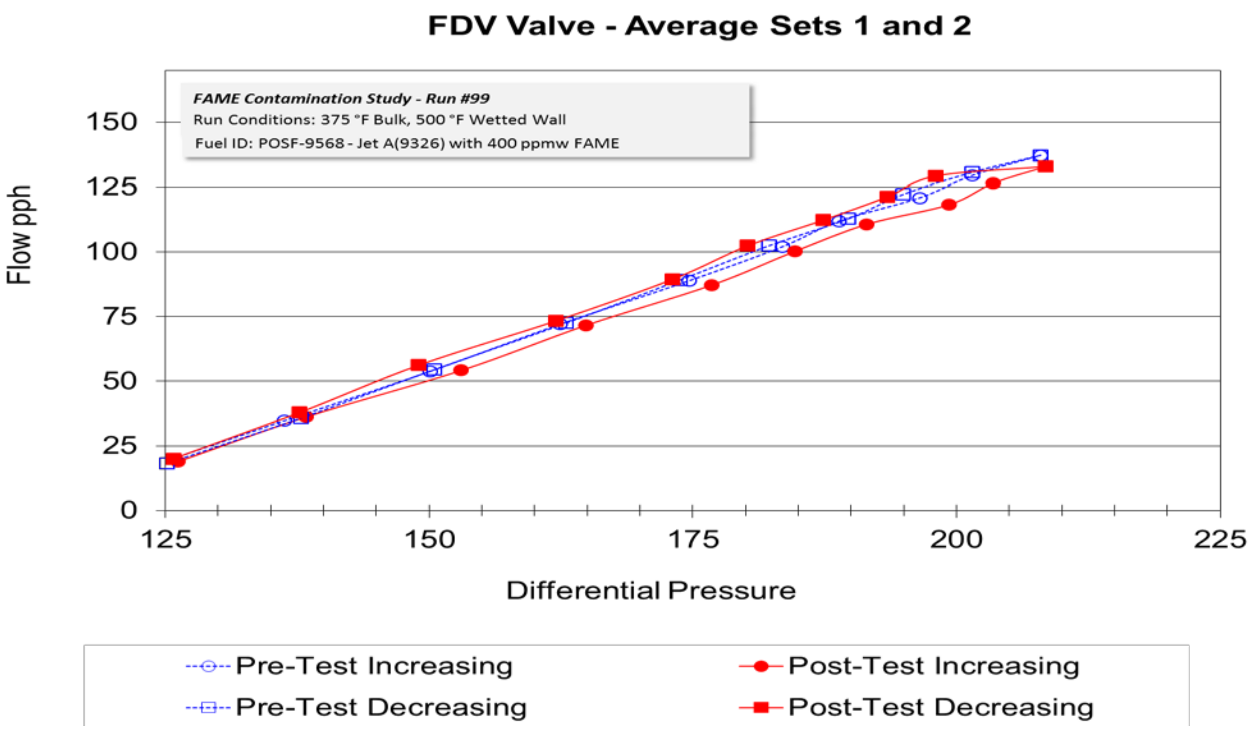


Figure E- 8 FDV Hysteresis, Run 99, 400 ppm FAME, HT Temperature Profile

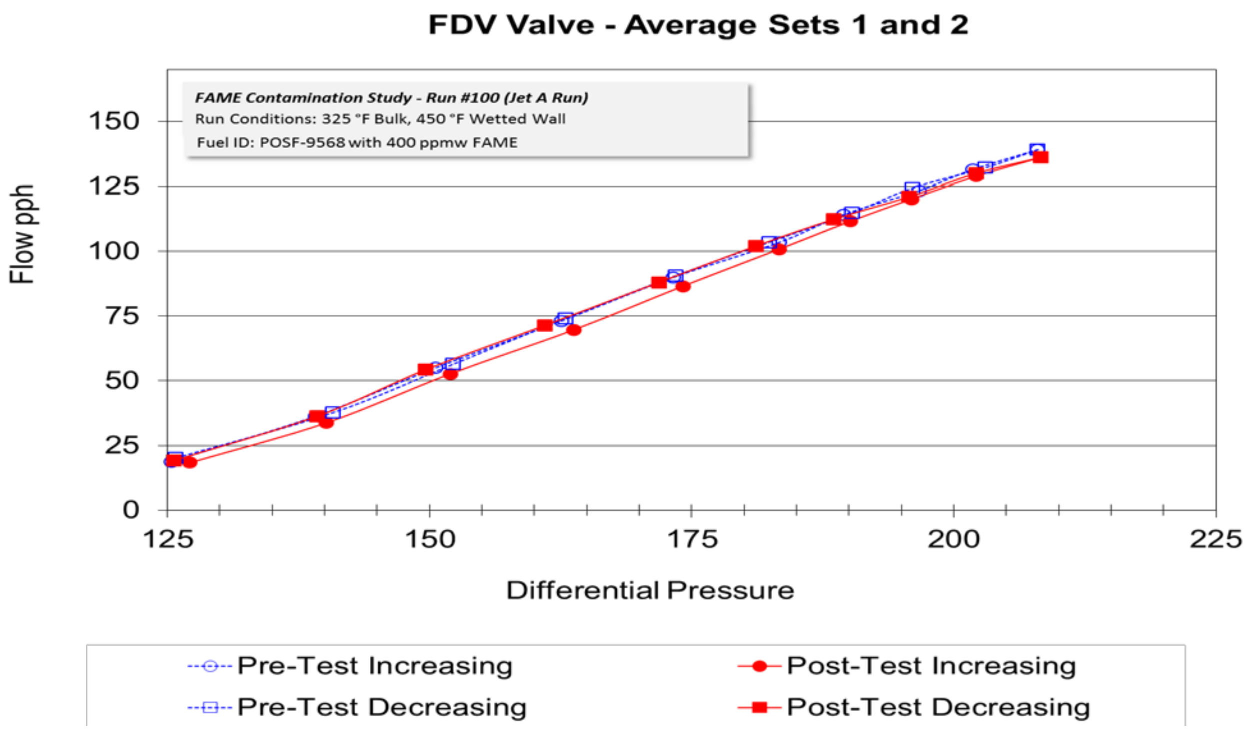


Figure E- 9 FDV Hysteresis, Run 100, 400 ppm FAME, LT Temperature Profile

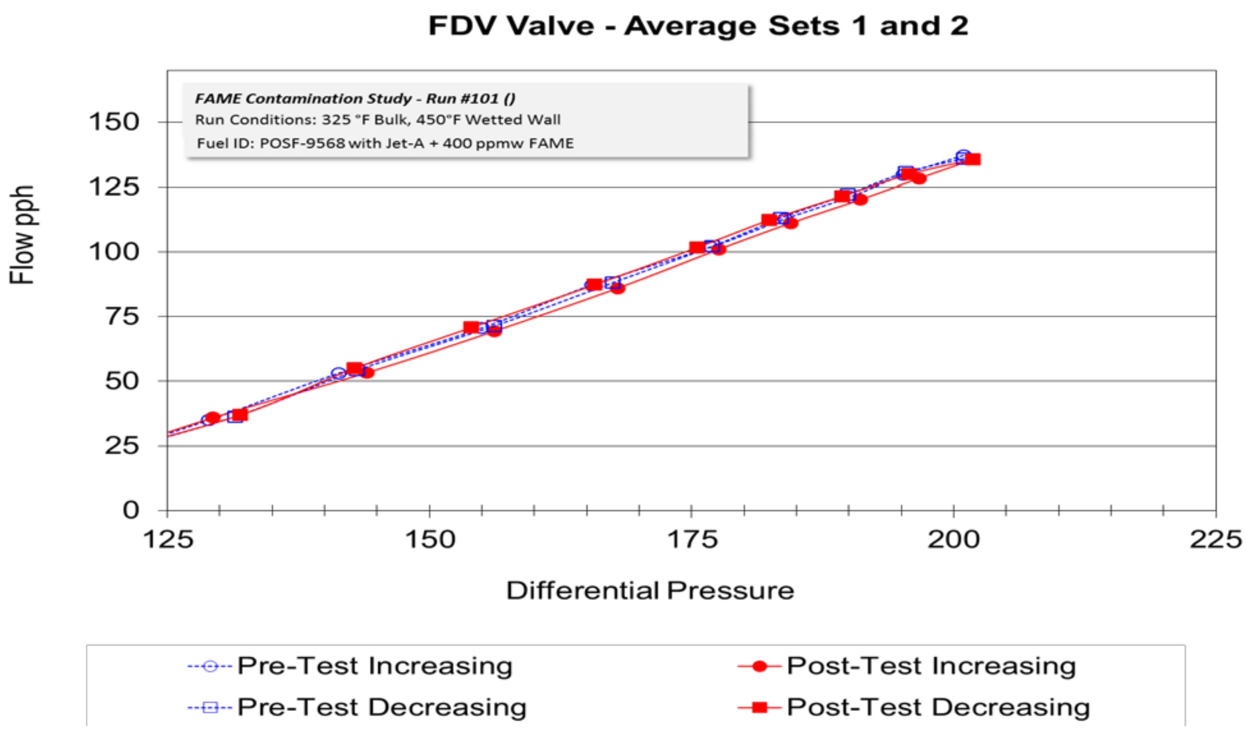


Figure E- 10 FDV Hysteresis, Run 101, 400 ppm FAME, LT Temperature Profile

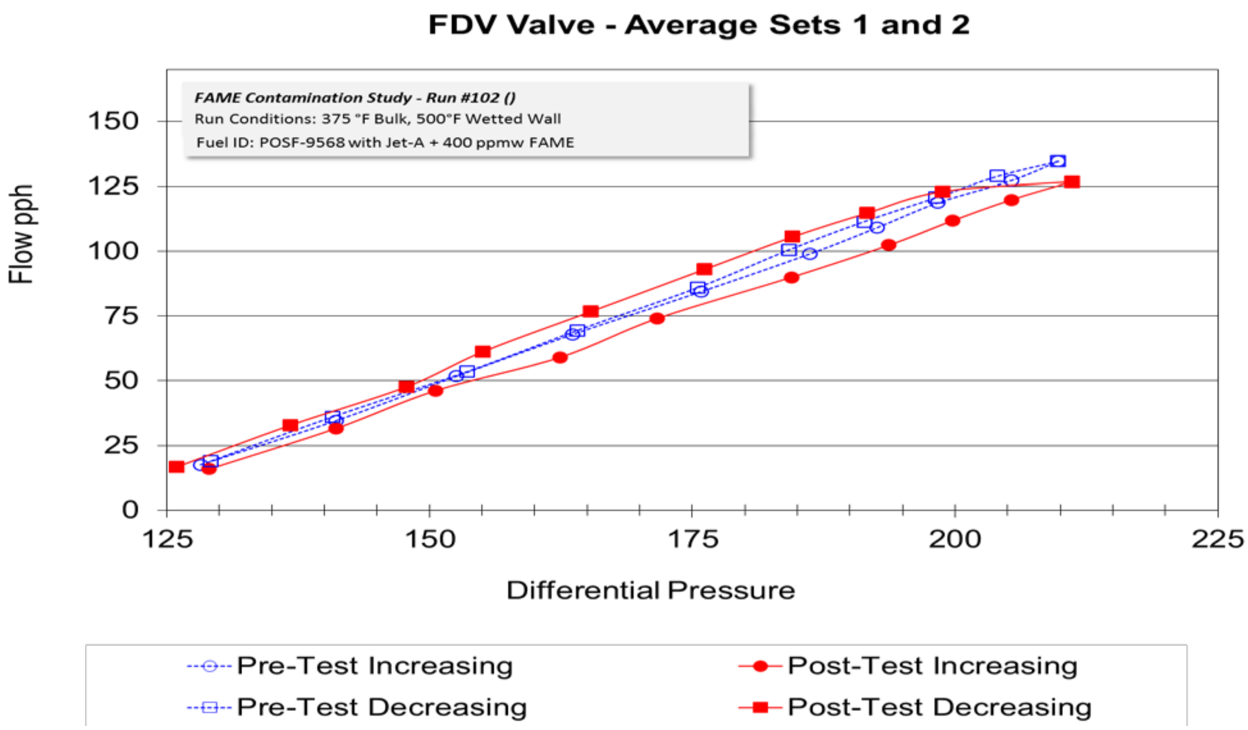


Figure E- 11 FDV Hysteresis, Run 102, 400 ppm FAME, HT Temperature Profile

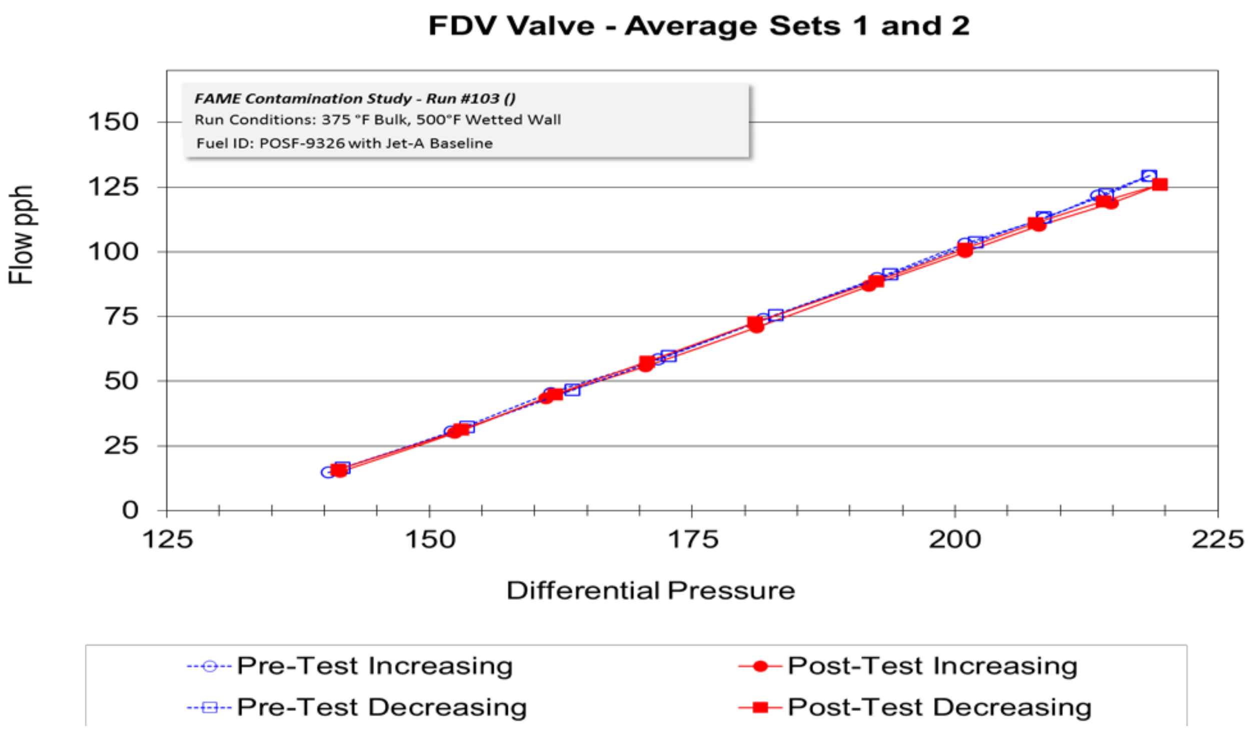


Figure E- 12 FDV Hysteresis, Run 103, Baseline Jet A, HT Temperature Profile

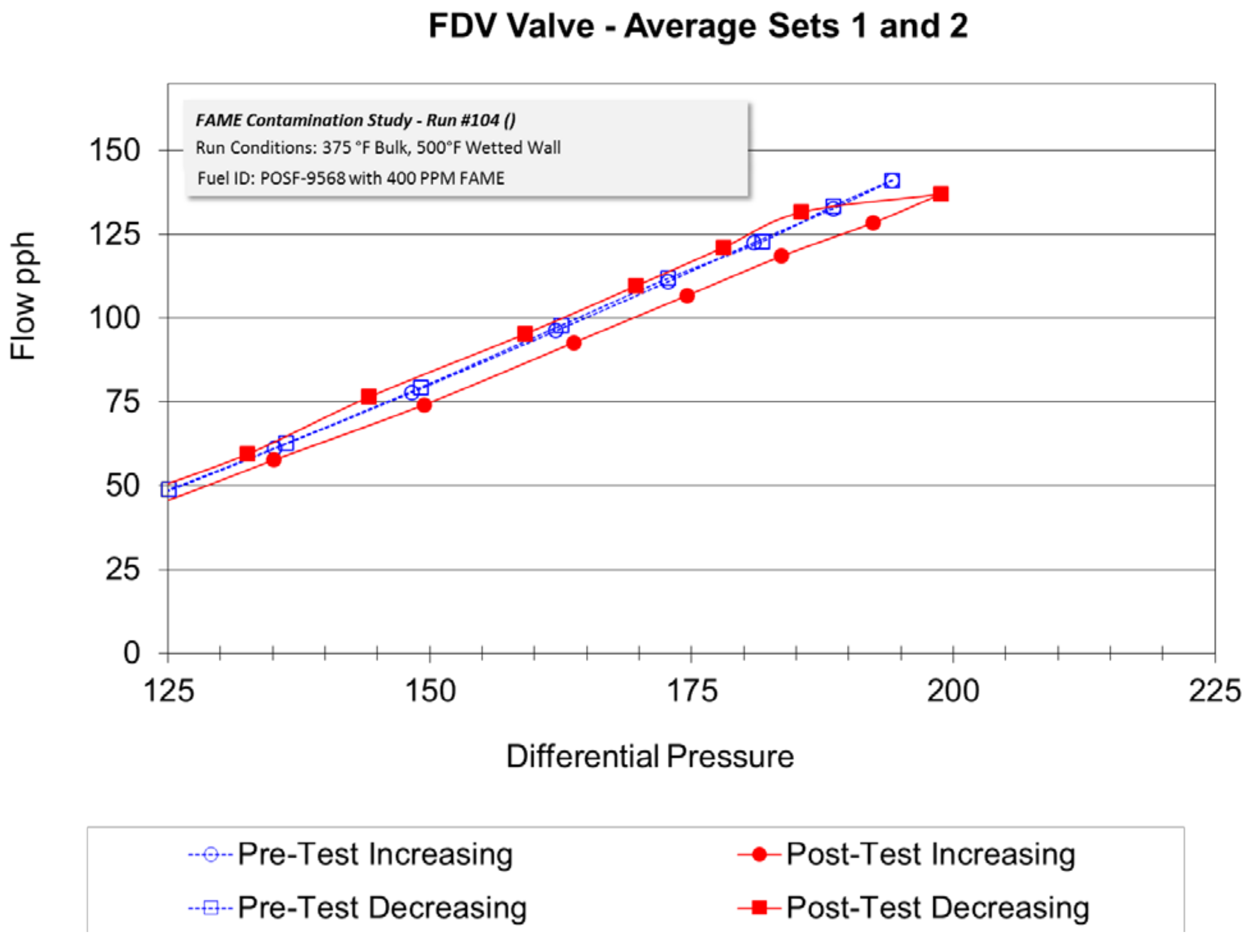


Figure E- 13 FDV Hysteresis, Run 104, 400 ppm FAME, HT Temperature Profile

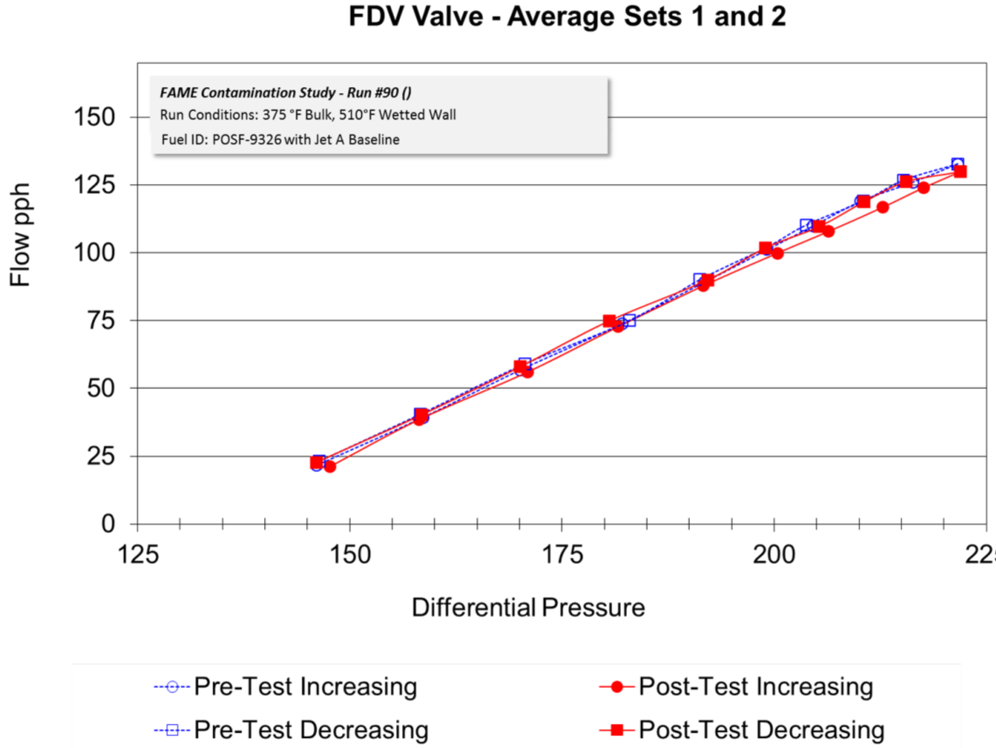


Figure E- 14 FDV Hysteresis, Run 90, Baseline, HT+ Temperature Profile, EDTST Protocol

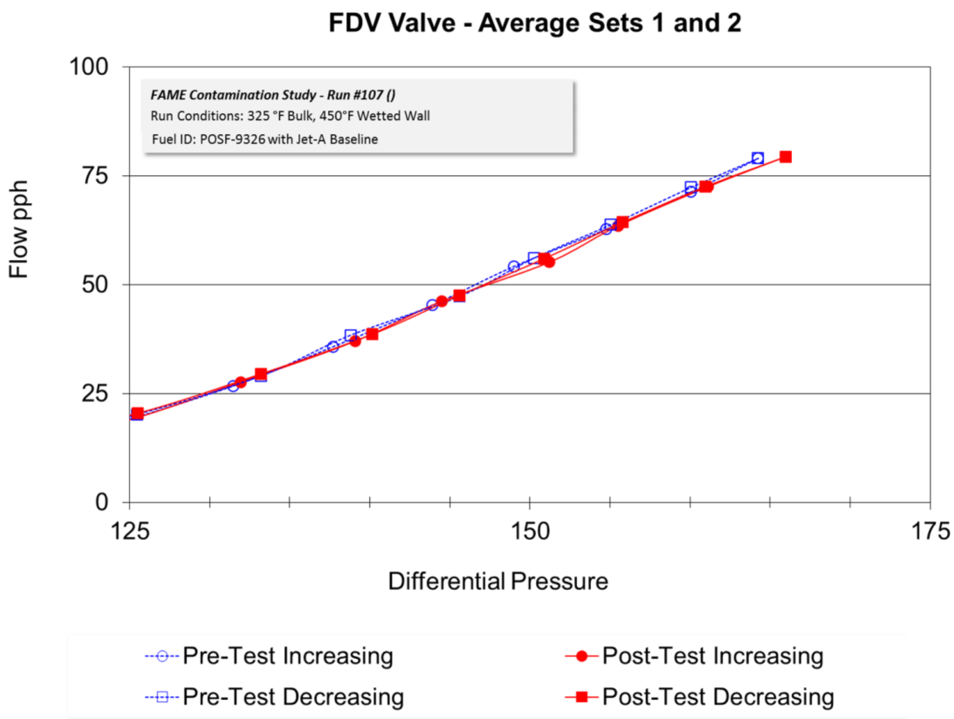


Figure E- 15 FDV Hysteresis, Run 107, Baseline, HT+ Temperature Profile, EDTST Protocol

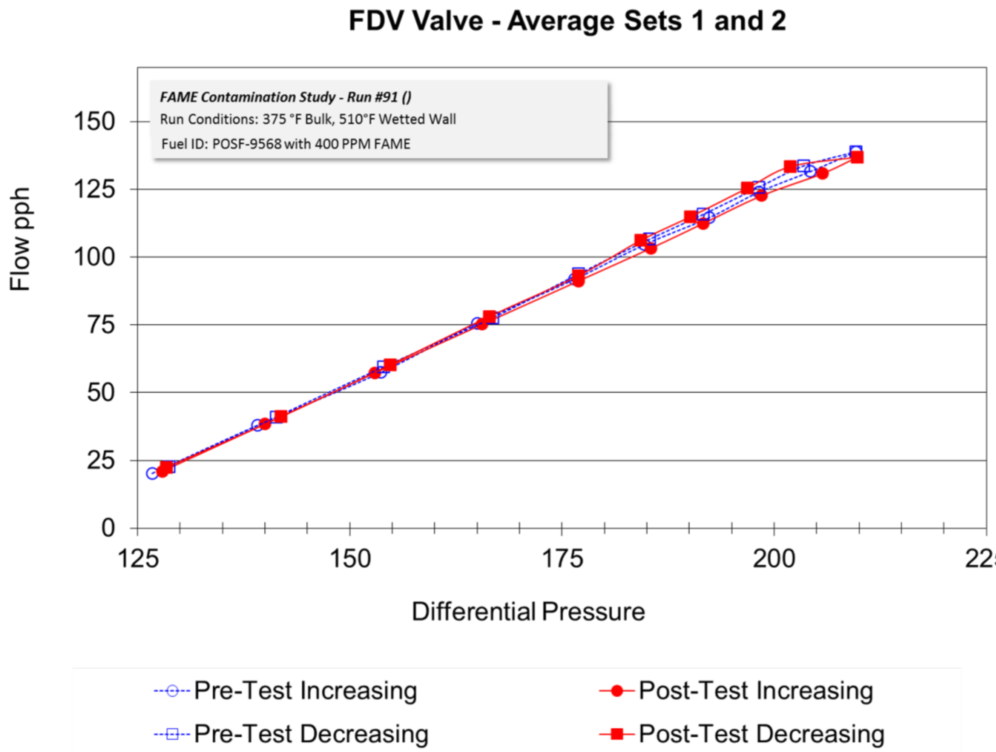


Figure E- 16 FDV Hysteresis, Run 91, FAME, HT+ Temperature Profile, EDTST Protocol

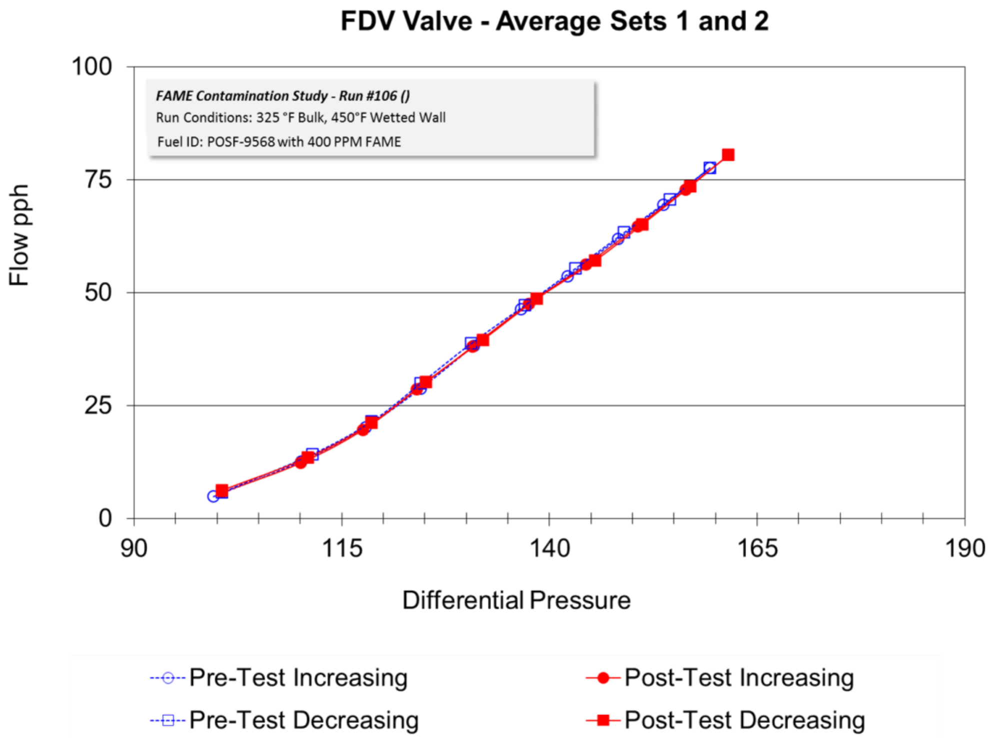


Figure E- 17 FDV Hysteresis, Run 106, FAME, HT+ Temperature Profile, EDTST Protocol

Appendix F - Servo Spool, Flow Divider Valve and Nozzle Simulator Deposition

The photos in this Appendix are grouped by the test article and test temperature profile and provide a comparison between baseline Jet A fuel and FAME-contaminated (400 ppm) fuel.

Servo Spool (HT)
JFTOT BP = 285 °C

BASELINE (HT) | FAME (HT)

Run 92

Servo 1 and 2 Spool

Run 95

Run 96

AFRL 54

Figure F- 1

Servo Spool (MT)
JFTOT BP = 285 °C

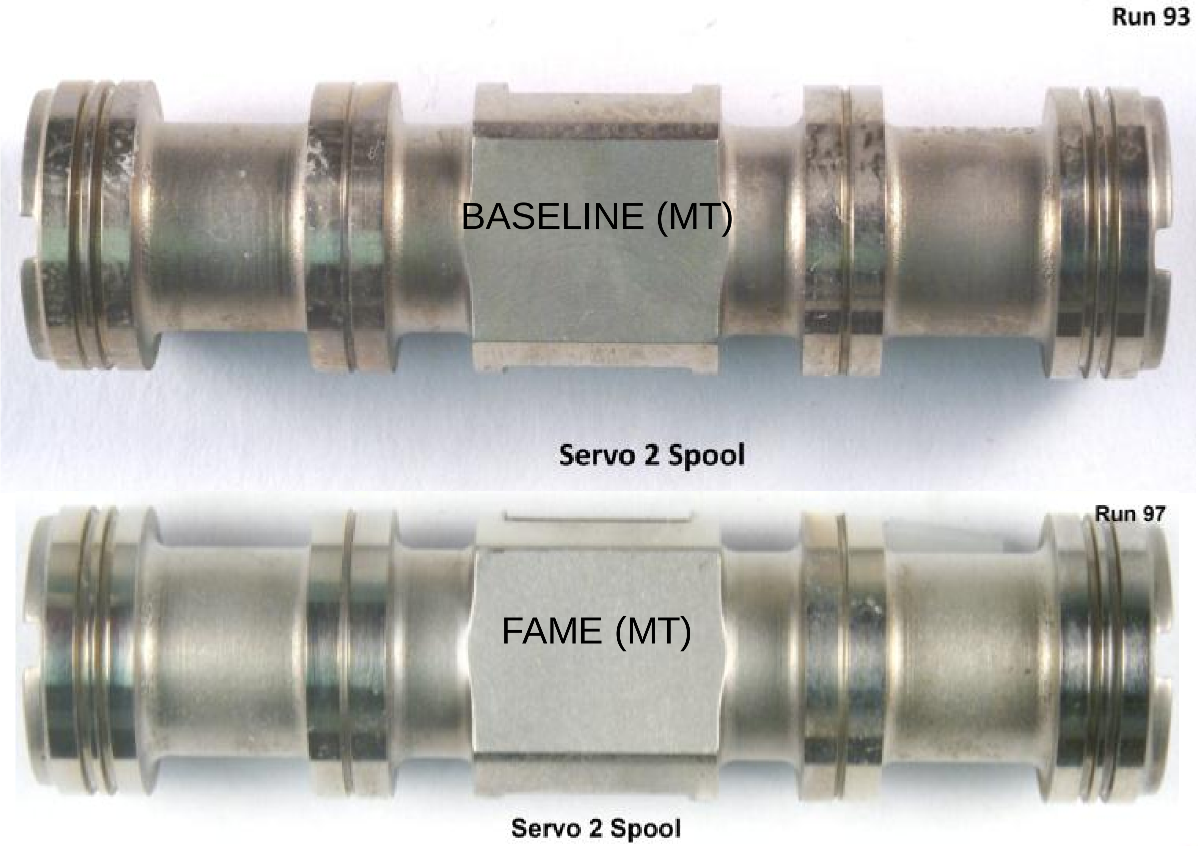


Figure F- 2

Servo Spool (LT)
JFTOT BP = 285 °C

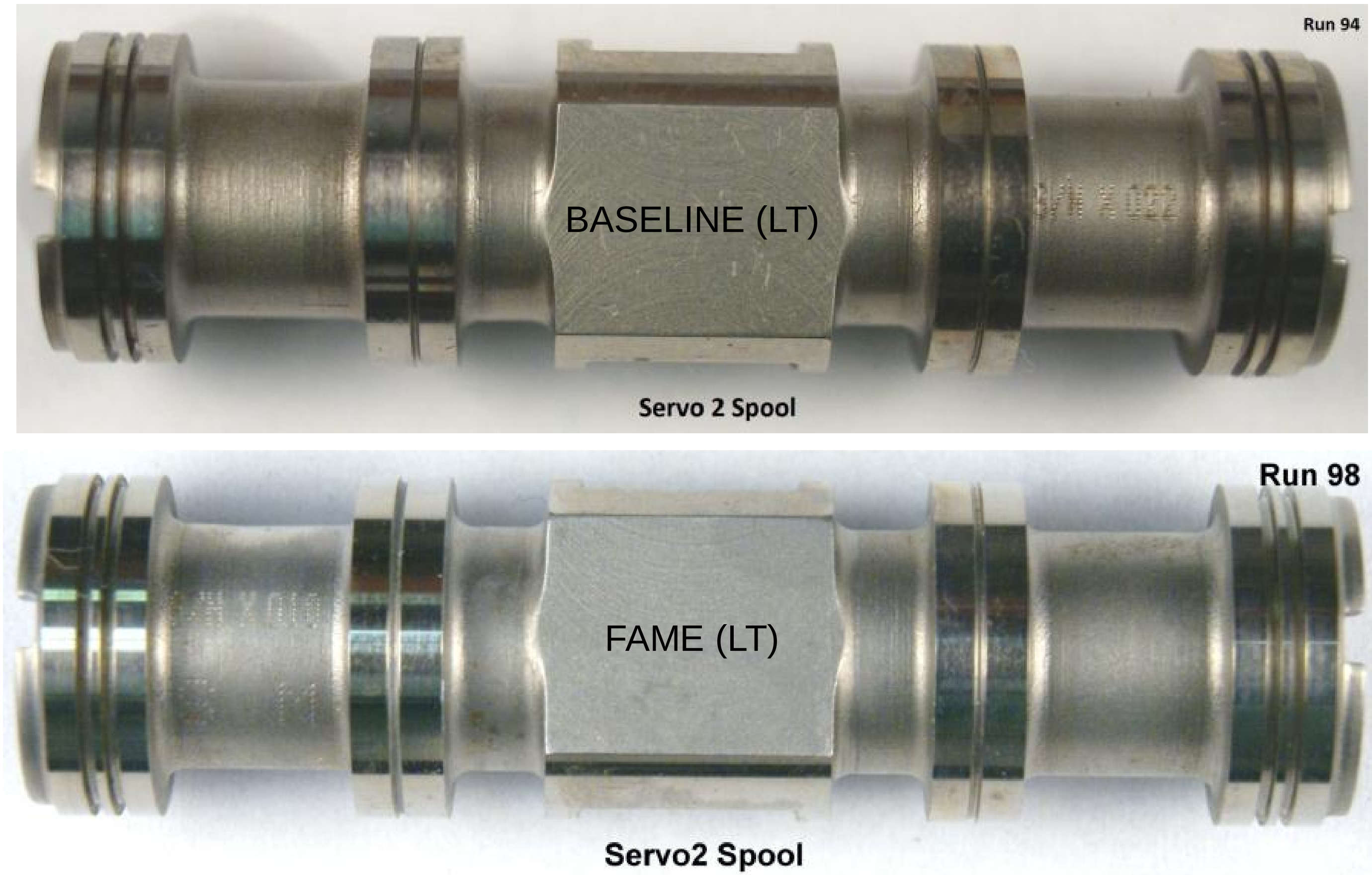


Figure F- 3

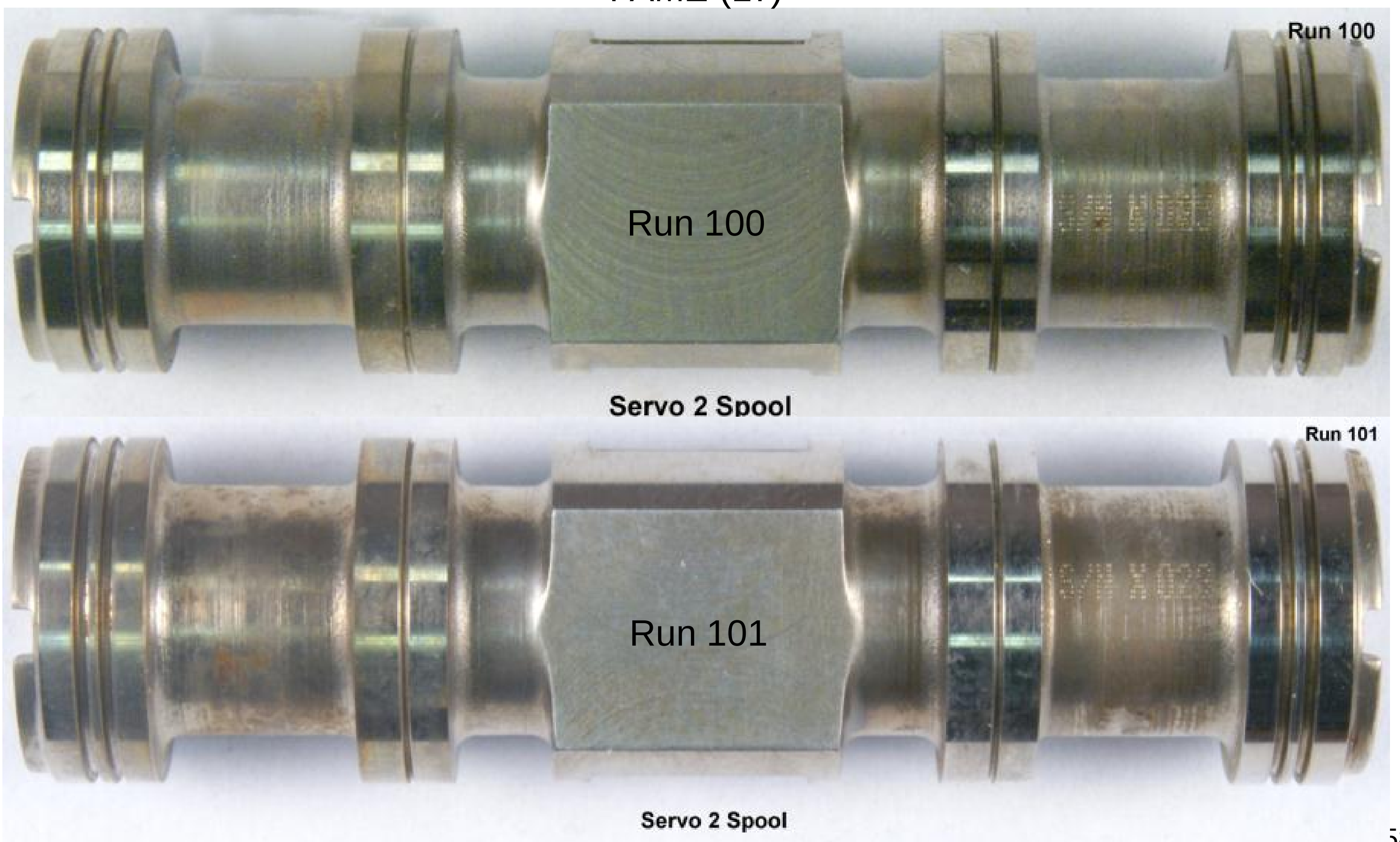
Servo Spool (HT)
JFTOT BP = 275 °C

BASELINE (HT) | FAME (HT)

Figure F- 4

Servo Spool (LT)
JFTOT BP = 275 °C

FAME (LT)



58

Figure F- 5

Servo Spools Compared
JFTOT BP = 285 °C

FAME (HT)

FAME (LT)

FAME (MT)

Figure F- 6

Servo Spool (HT-LT Compared)
JFTOT BP = 275 °C

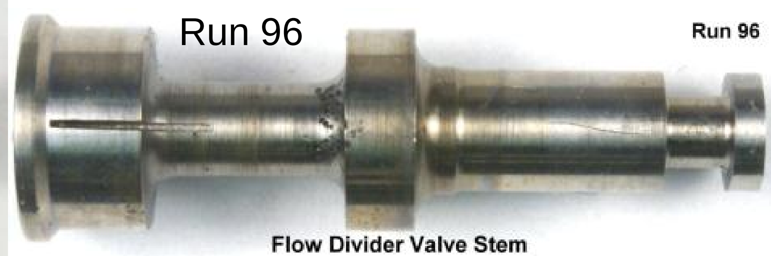
FAME (HT) FAME (LT)

Figure F- 7

FDV Valve Stem (HT)
JFTOT BP = 285 °C

BASELINE (HT)

FAME (HT)



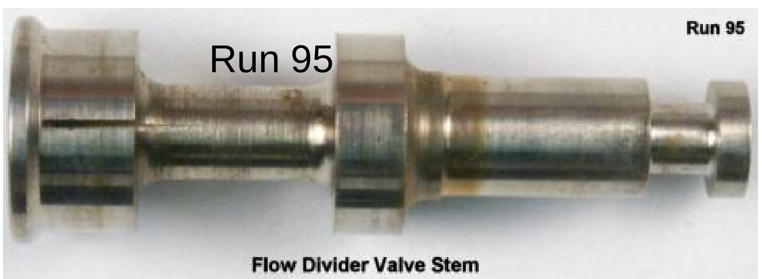


Figure F- 8

FDV Valve Stem (MT)
JFTOT BP = 285 °C

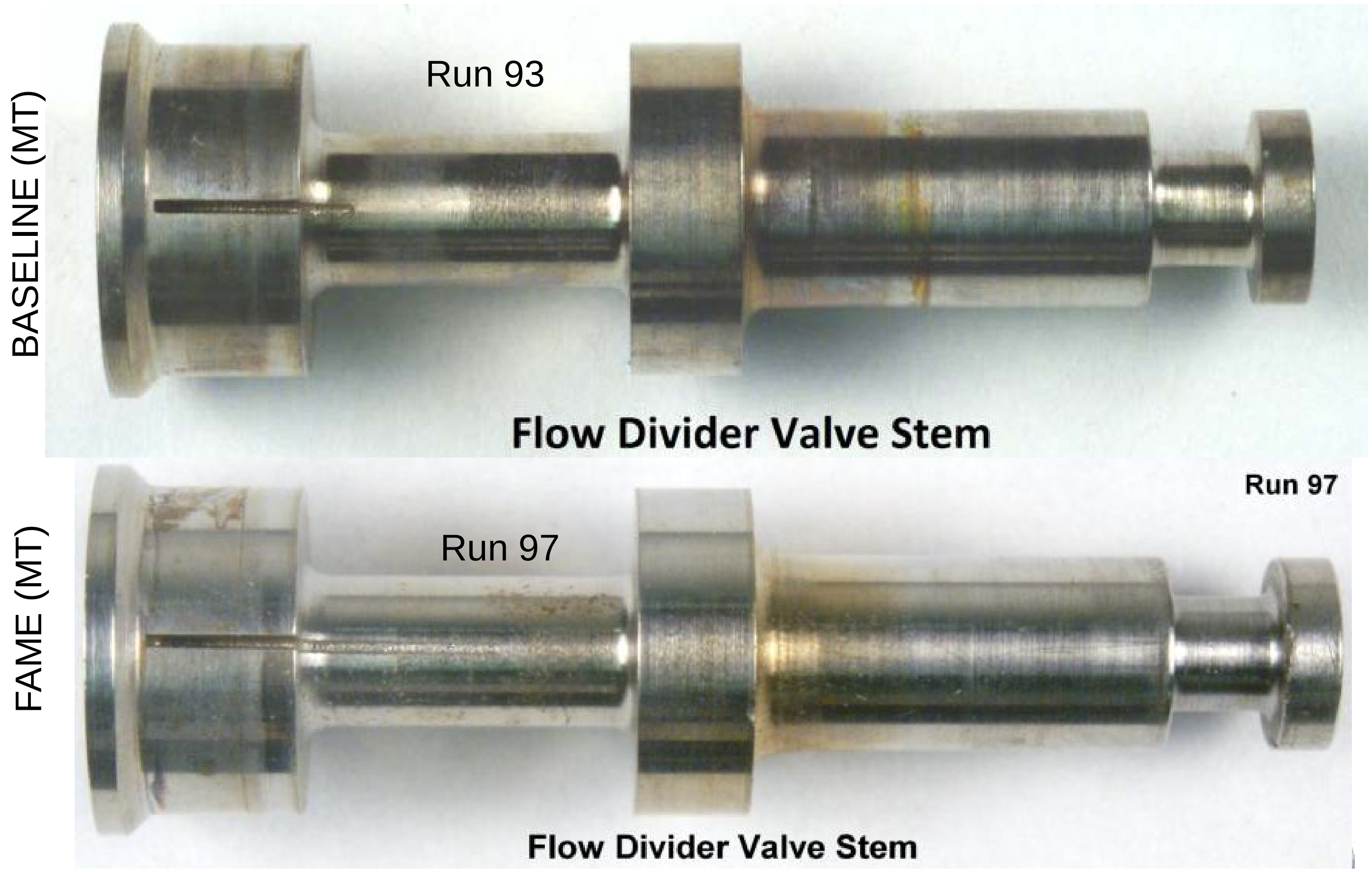


Figure F- 9

FDV Valve Stem (LT)
JFTOT BP = 285 °C

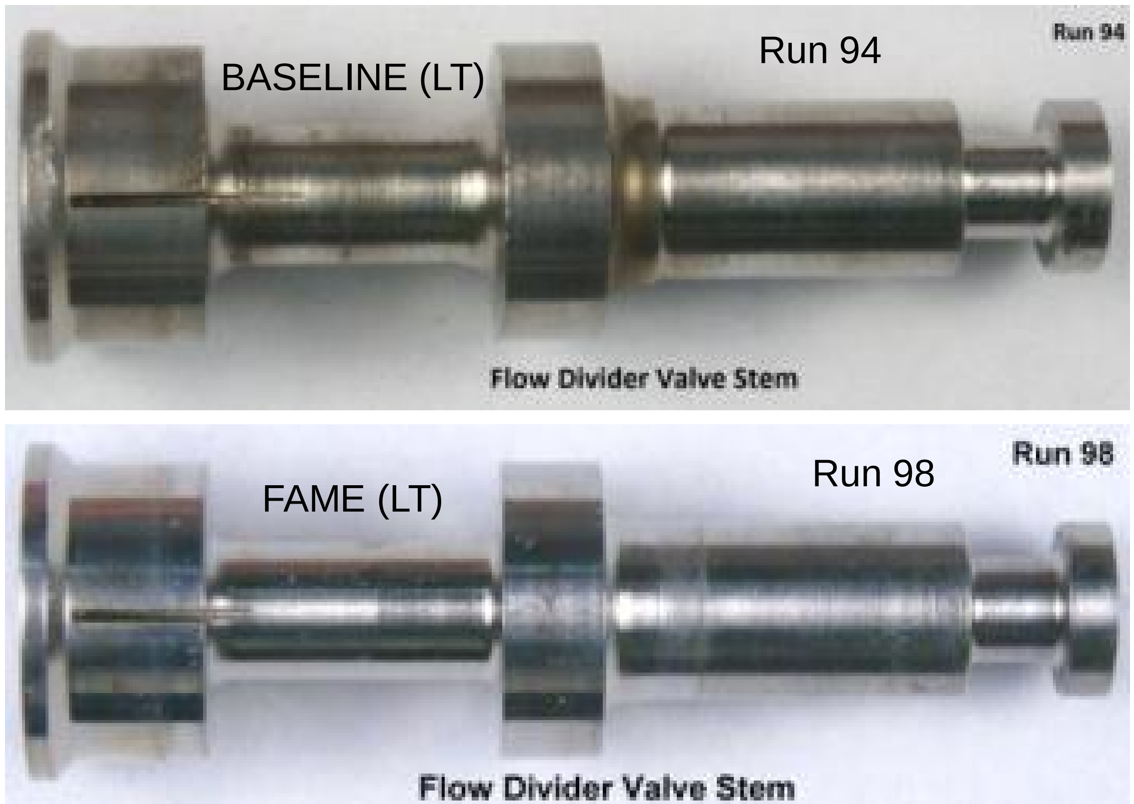
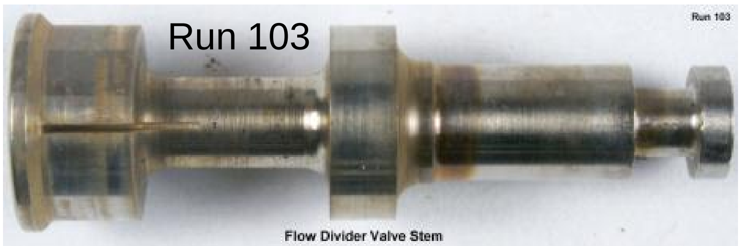


Figure F- 10

FDV Valve Stem (HT)
JFTOT BP = 275 °C

BASELINE (HT)

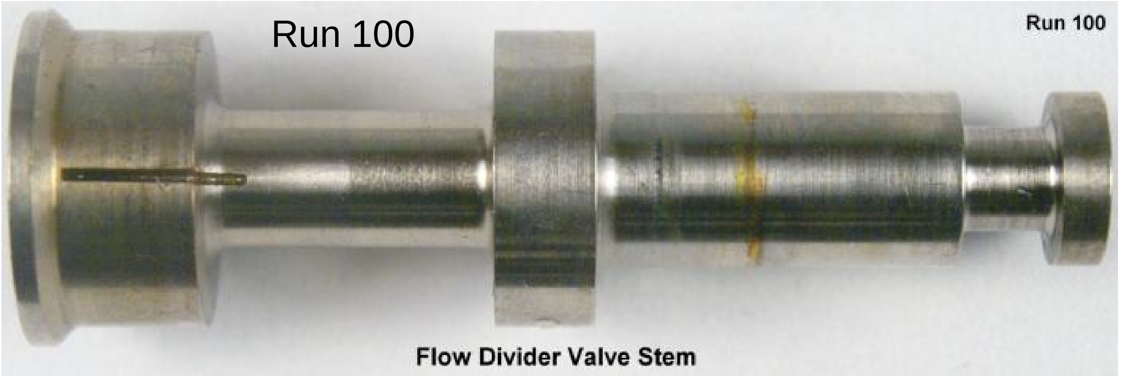


FAME (HT)

Figure F- 11

FDV Valve Stem (LT)
JFTOT BP = 275 °C

FAME (LT)



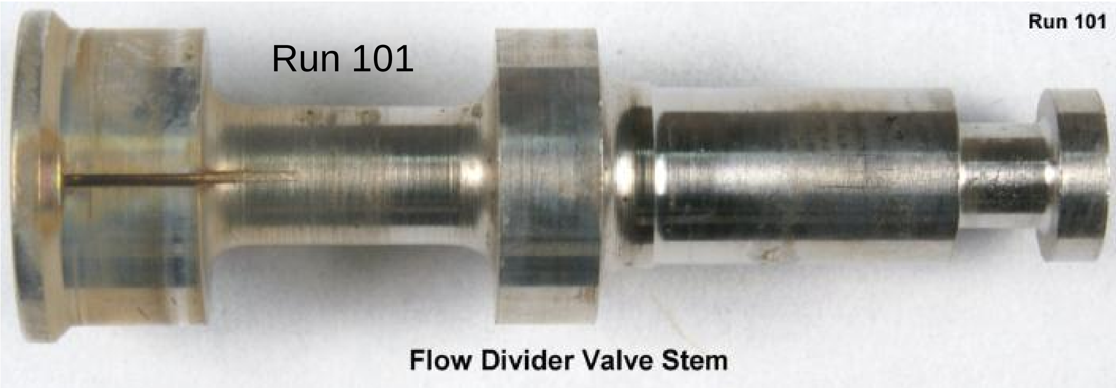
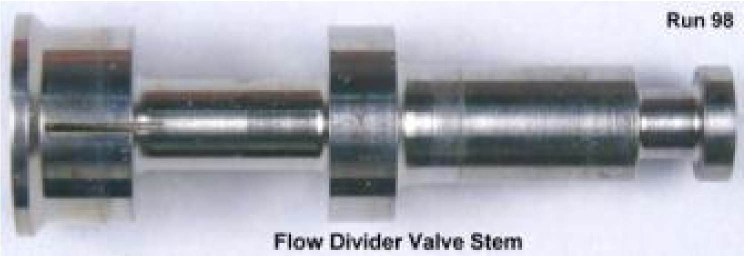


Figure F- 12

FDV Valve Stems Compared
JFTOT BP = 285 °C

FAME (HT)

FAME (LT)



FAME (MT)

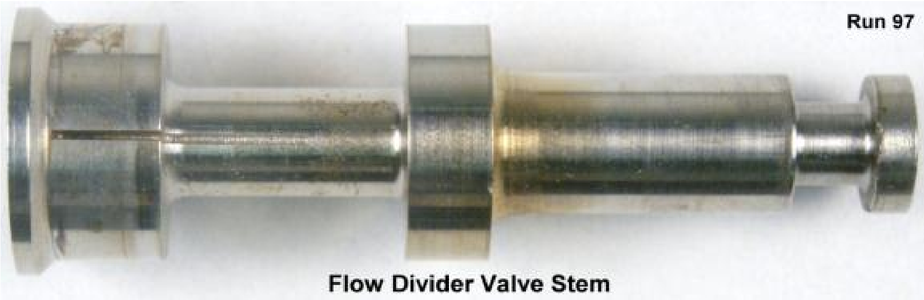
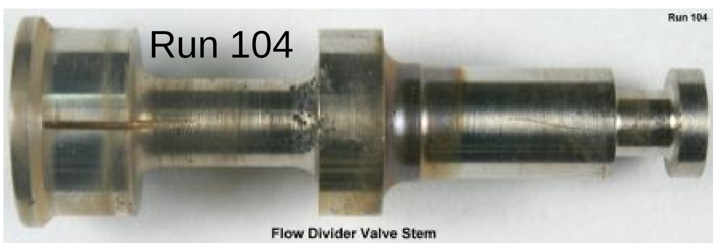


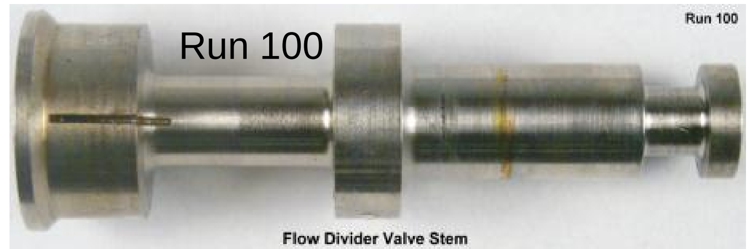
Figure F- 13

FDV Valve Stem (HT-LT Compared) JFTOT BP = 275 °C

FAME (HT)



FAME (LT)



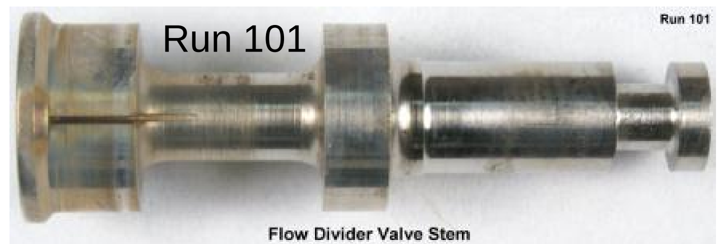


Figure F- 14

FDV Screen (HT)
JFTOT BP = 285 °C

BASELINE (HT)

FAME (HT)

Figure F- 15

FDV Screen (MT)
JFTOT BP = 285 °C

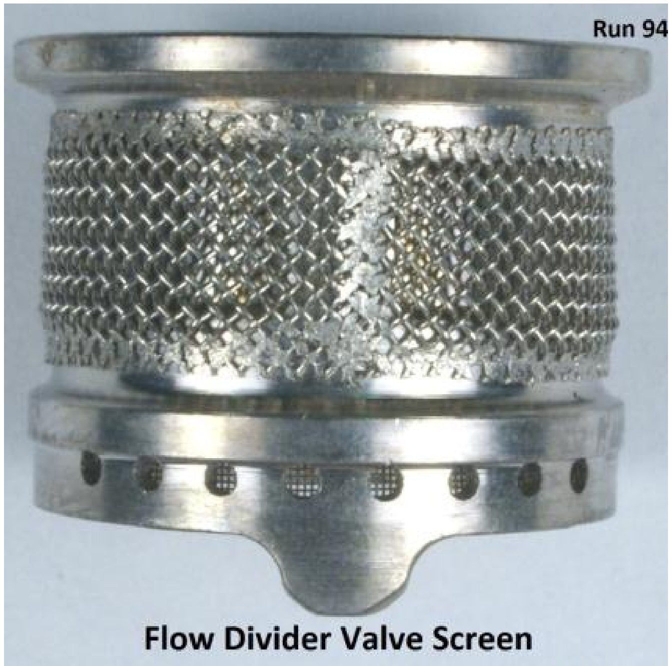
BASELINE (MT)

FAME (MT)

Figure F- 16

FDV Screen (LT)
JFTOT BP = 285 °C

BASELINE (LT)



FAME (LT)

Figure F- 17

FDV Screen (HT)
JFTOT BP = 275 °C

BASELINE (HT)

FAME (HT)

Run 99

Run 104

Run 102

Figure F- 18

FDV Screen (LT)
JFTOT BP = 275 °C

FAME (LT)

Figure F- 19

FDV Screens Compared
JFTOT BP = 285 °C

FAME (HT)

FAME (LT)

FAME (MT)

Figure F- 20

FDV Valve Stem (HT-LT Compared)
JFTOT BP = 275 °C

FAME (HT)

Run 99

Run 104

Run 102

FAME (LT)

Run 100

Run 101

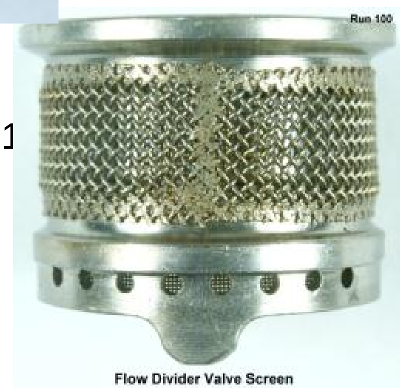


Figure F- 21

Nozzle Components (HT)
JFTOT BP = 285 °C

BASELINE (HT)

FAME (HT)

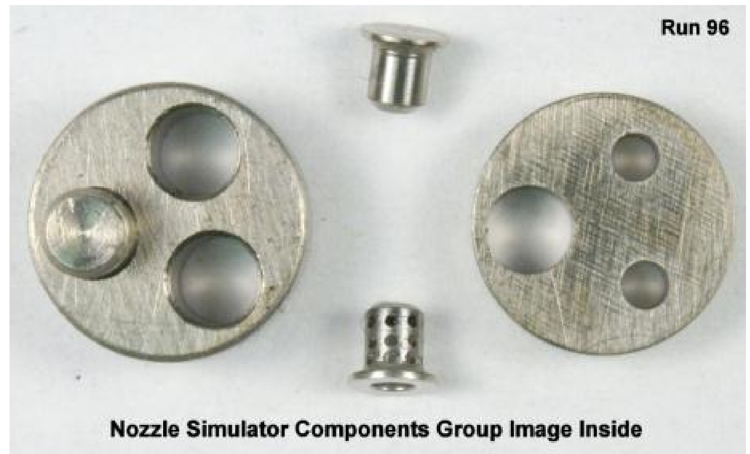


Figure F- 22

Nozzle Components (MT)
JFTOT BP = 285 °C

BASELINE (MT)

FAME (MT)

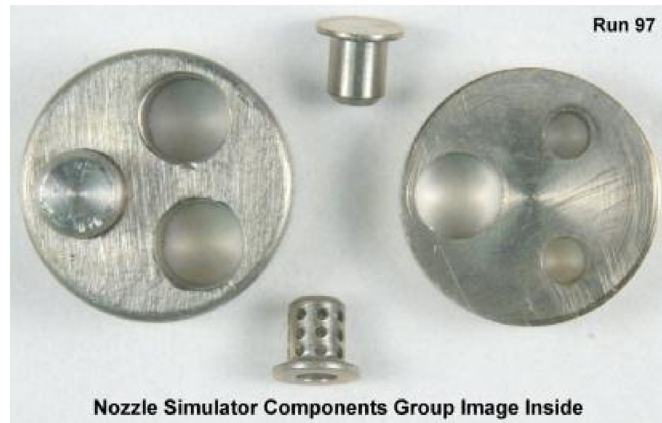


Figure F- 23

Nozzle Components (LT)
JFTOT BP = 285 °C

BASELINE (LT)

FAME (LT)

Figure F- 24

Nozzle Components (HT)
JFTOT BP = 275 °C

BASELINE (HT)

FAME (HT)

Run 99

Run 102

Run 104

Figure F- 25

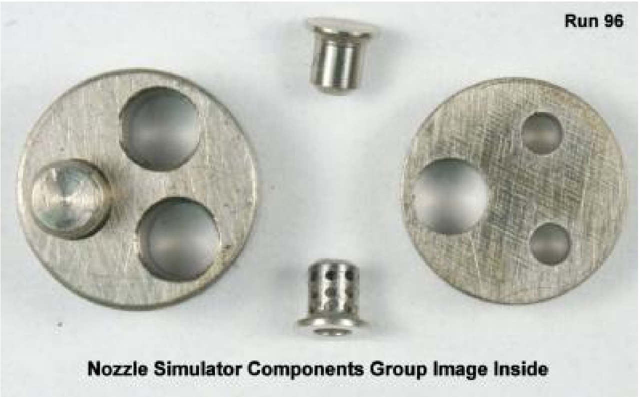
Nozzle Components (LT)
JFTOT BP = 275 °C

FAME (LT)

Figure F- 26

Nozzle Components Compared
JFTOT BP = 285 °C

FAME (HT)



FAME (LT)

FAME (MT)

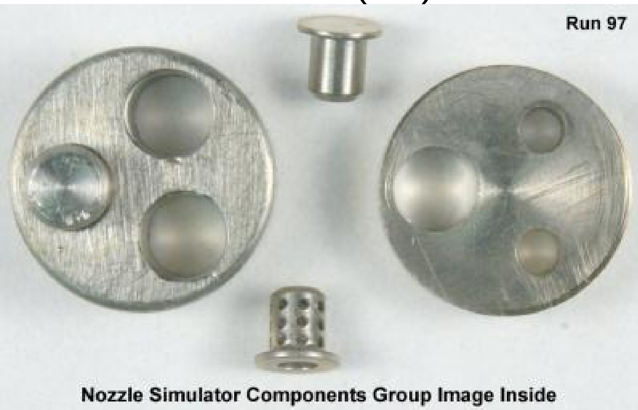


Figure F- 27

Nozzle Components Compared
JFTOT BP = 275 °C

Figure F- 28

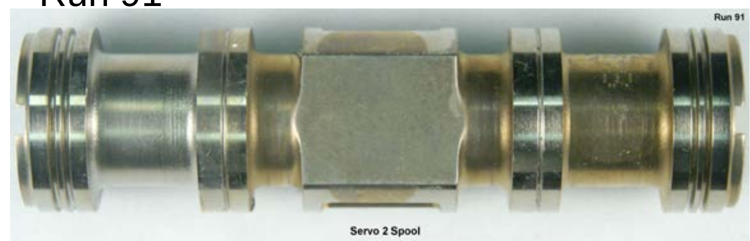
Servo Valve Spool Visual Deposition
EDTST Protocol Runs (90, 91, 106 & 107)

BASELINE FUEL

FAME-CONTAMINATED FUEL

Run 90

Run 91



Run 107

Run 106

Figure F- 29

FDV Stem Visual Deposition
EDTST Protocol Runs (90, 91, 106 & 107)

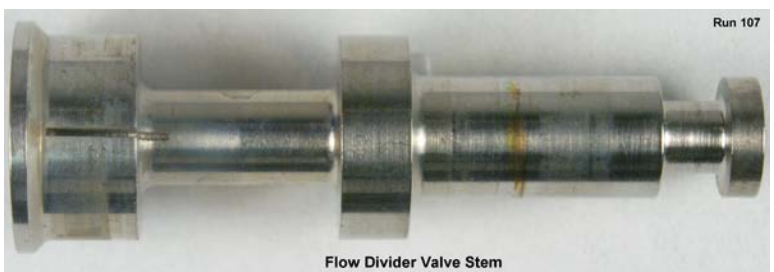
BASELINE FUEL

FAME-CONTAMINATED FUEL

Run 90

Run 91

Run 107



Run 106

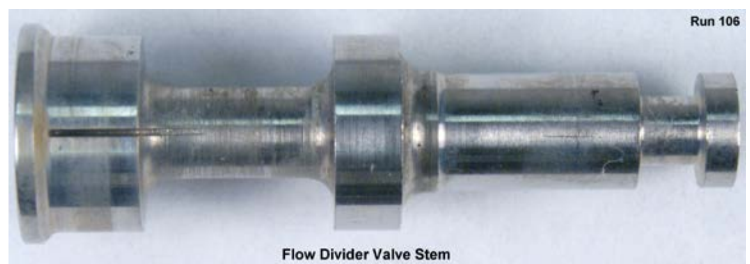


Figure F- 30

FDV Screen Visual Deposition
EDTST Protocol Runs (90, 91, 106 & 107)

BASELINE FUEL

FAME-CONTAMINATED FUEL

Run 90

Run 91

Run 107

Run 106

Figure F- 31

Nozzle Screen Simulator Visual Deposition
EDTST Protocol Runs (90, 91, 106 & 107)

BASELINE FUEL

Run 90

FAME-CONTAMINATED FUEL

Run 91

Run 107

Run 106

Figure F- 32

Appendix G – HP Pump Fuel Filter Visual Inspection

The photos in this Appendix provide a comparison between the baseline Jet A and FAME-contaminated (400 ppm) fuels.

HP Pump Filter Visual Inspection
LDSF Protocol Runs (103 and 104)

BASELINE FUEL | FAME-CONTAMINATED FUEL

Run 103 | Run 104

Figure G- 1 - Comparison of JP Pump Filters for GDTC Runs 103 (Baseline, HT) and 104 (FAME, HT)

HP Pump Filter Visual Inspection

EDTST Protocol Runs (90, 91, 106 & 107)

BASELINE FUEL, HT CONDITIONS

FAME-CONTAMINATED FUEL, HT CONDITIONS

Run 90

Run 91

Not present in Baseline Fuel Filters

Run 107

Run 106

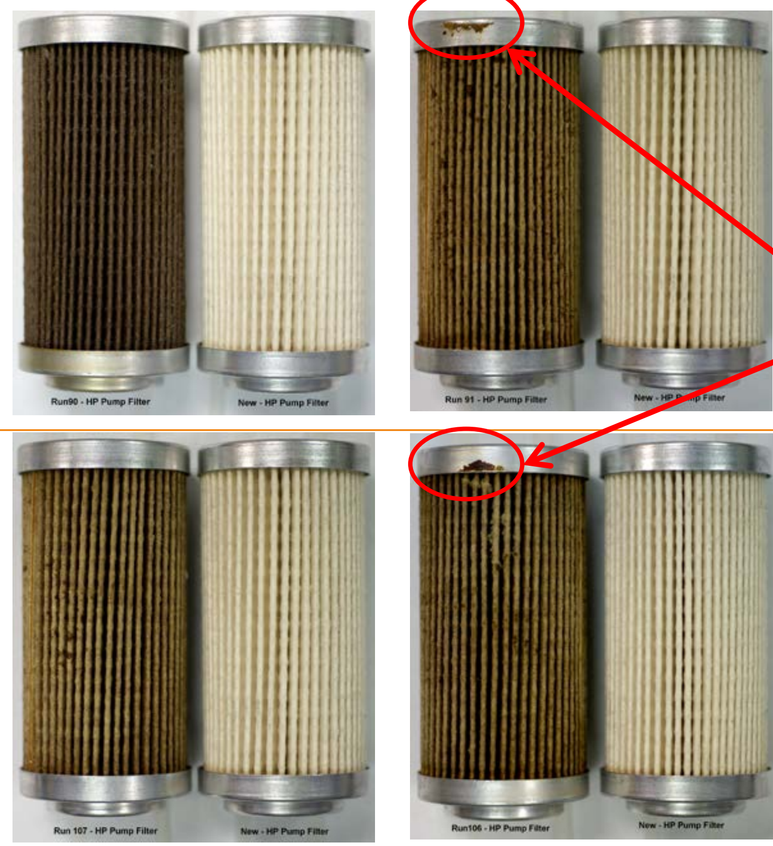
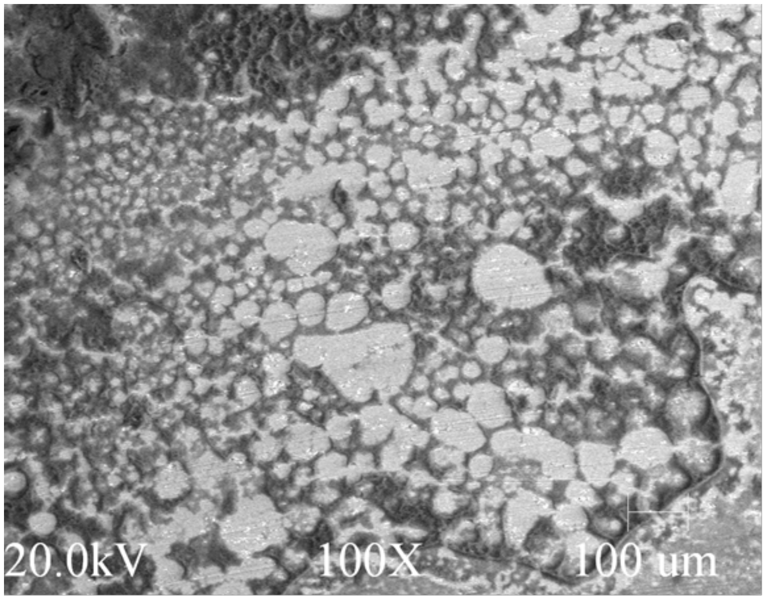
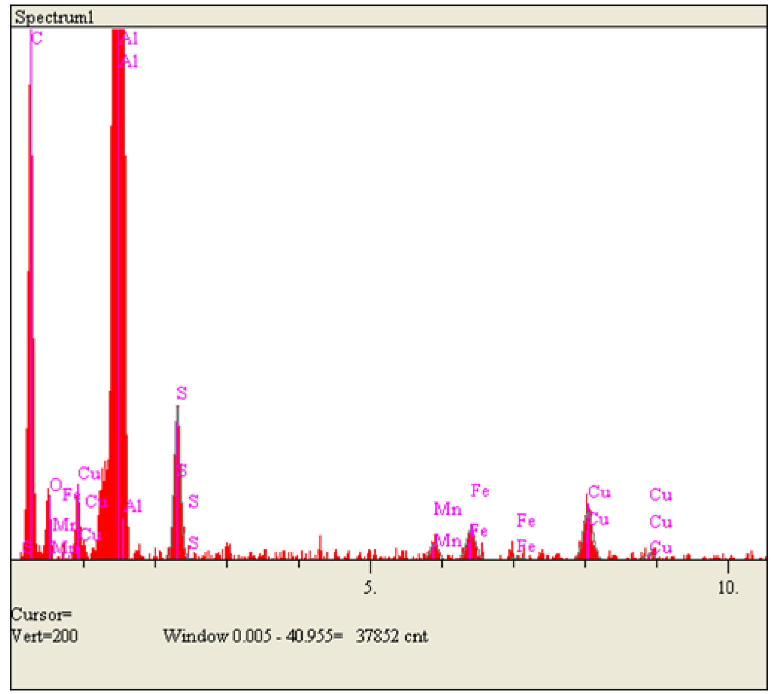


Figure G- 2 – HP Pump Filter Comparison, EDTST Protocol, HT+ Conditions

Analysis of "Brown Goo"
HP Pump Filter





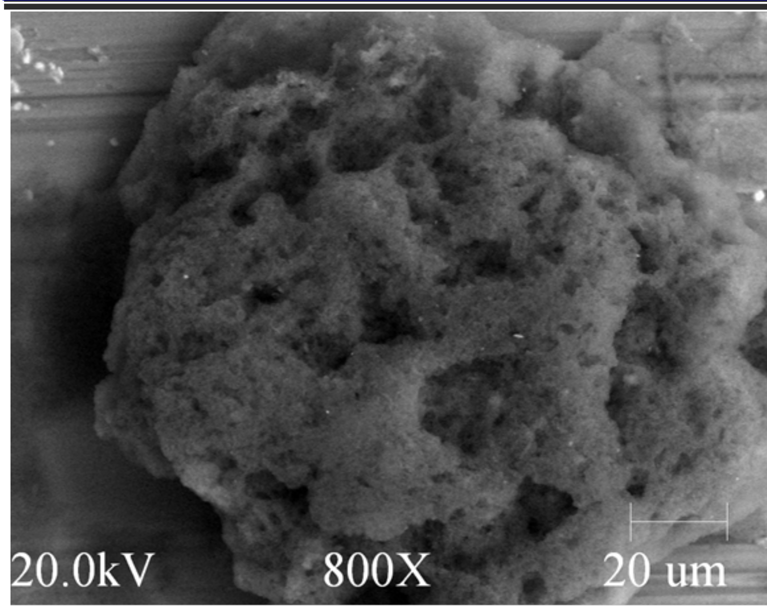
Elt.	Line	Intensity (c/s)	Error 2-sig	Conc	Units	
S	Ka	9.62	0.763	29.933	wt.%	
Mn	Ka	1.48	0.299	6.948	wt.%	
Fe	Ka	2.70	0.404	14.465	wt.%	
Cu	Ka	4.70	0.534	48.654	wt.%	
				100.000	wt.%	Total

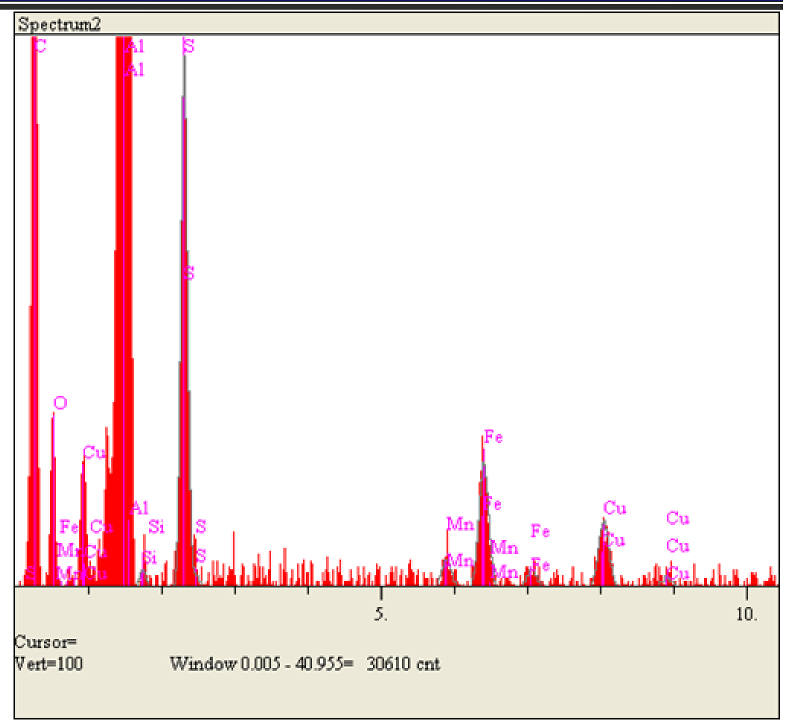
FINDING

Carbon-containing amorphous material with metals and non-metals contamination

Figure G- 3 – Carbon-Type Amorphous Material with Metalic and Non-Metalic Constituents

Analysis of “Brown Goo”
HP Pump Filter





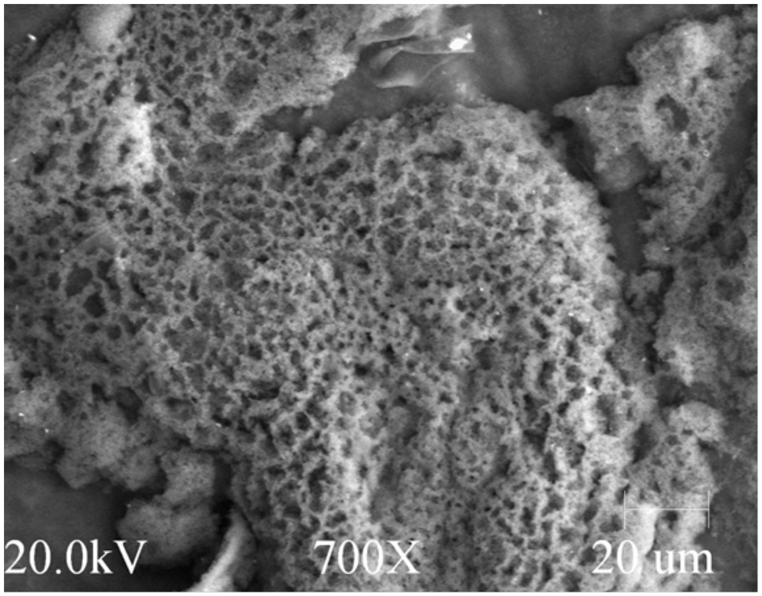
Elt.	Line	Intensity (c/s)	Error 2-sig	Conc	Units	
Si	Ka	0.53	0.178	1.453	wt.%	
S	Ka	16.16	0.989	40.409	wt.%	
Mn	Ka	1.15	0.264	4.729	wt.%	
Fe	Ka	5.33	0.568	26.163	wt.%	
Cu	Ka	3.03	0.428	27.246	wt.%	
				100.000	wt.%	Total

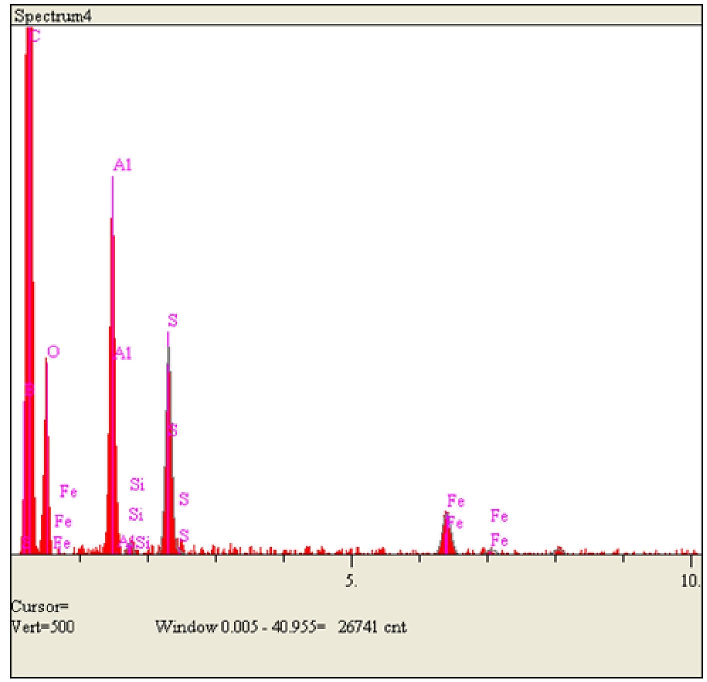
FINDING

Carbon-containing amorphous material with metals and non-metals contamination

Figure G- 4– Carbon-Type Amorphous Material with Metalic and Non-Metalic Constituents

Analysis of “Brown Goo”
HP Pump Filter





Elt.	Line	Intensity (c/s)	Error 2-sig	Conc	Units	
Si	Ka	1.77	0.327	2.924	wt.%	
S	Ka	33.03	1.415	53.486	wt.%	
Mn	Ka	0.34	0.143	0.977	wt.%	
Fe	Ka	9.39	0.755	33.489	wt.%	
Cu	Ka	1.44	0.296	9.124	wt.%	
				100.000	wt.%	Total

FINDING

Carbon-containing amorphous material with metals and non-metals contamination

Figure G- 5– Carbon-Type Amorphous Material with Metalic and Non-Metalic Constituents

Analysis of “Brown Goo”
HP Pump Filter

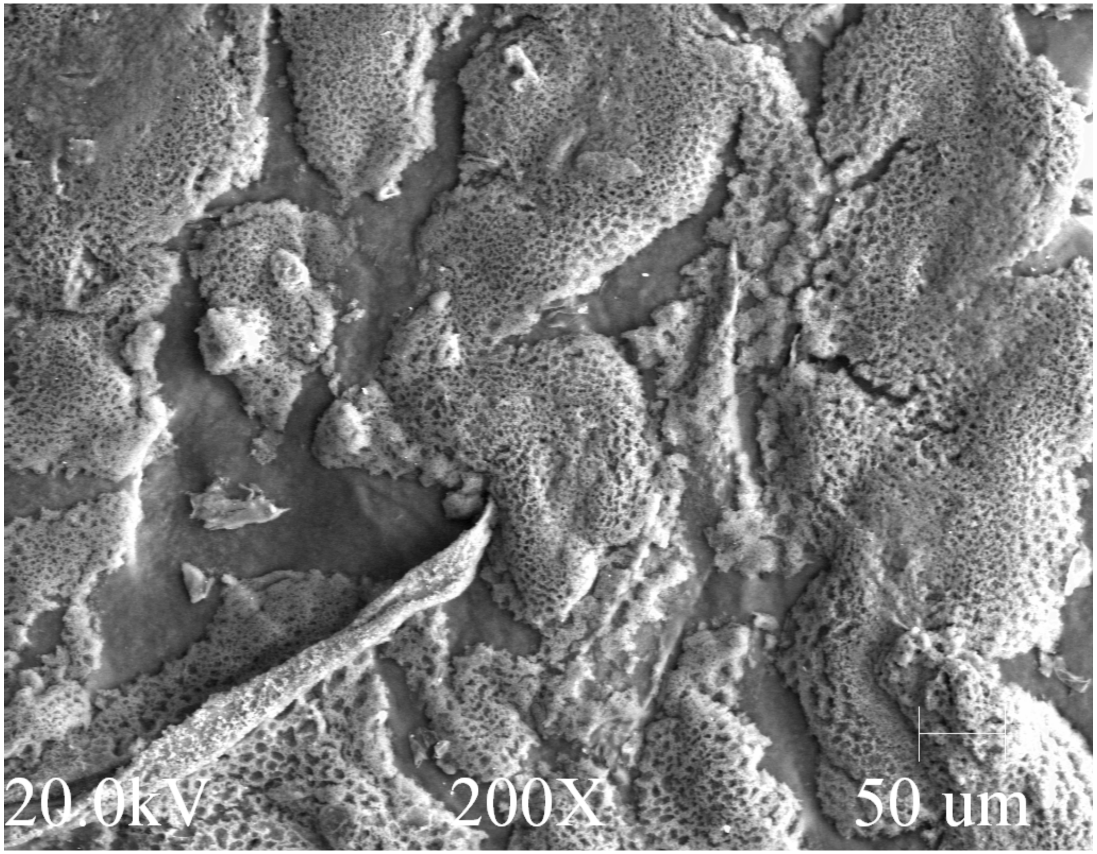
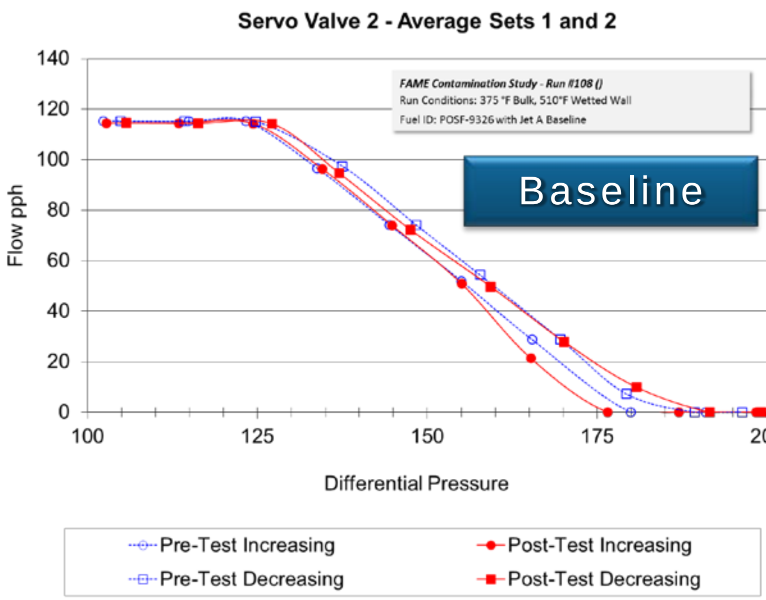


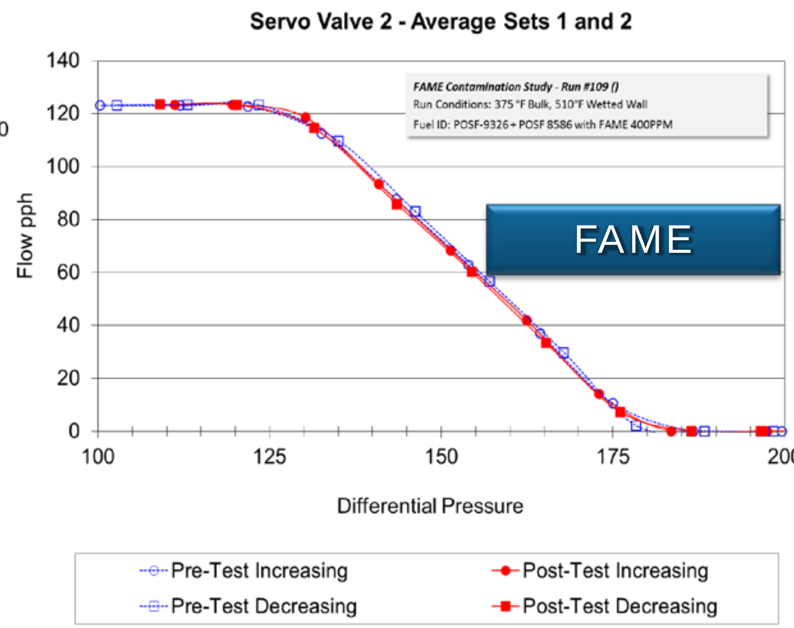
Figure G- 6 Carbon-Type Amorphous Material with Metalic and Non-Metalic Constituents

Appendix H – Additional Post-Program Testing to Evaluate Impact of FAME on Typical Jet A of Reasonable Thermal Stability

EDTST Mode Servo Hysteresis
FAME-Sensitive Fuel



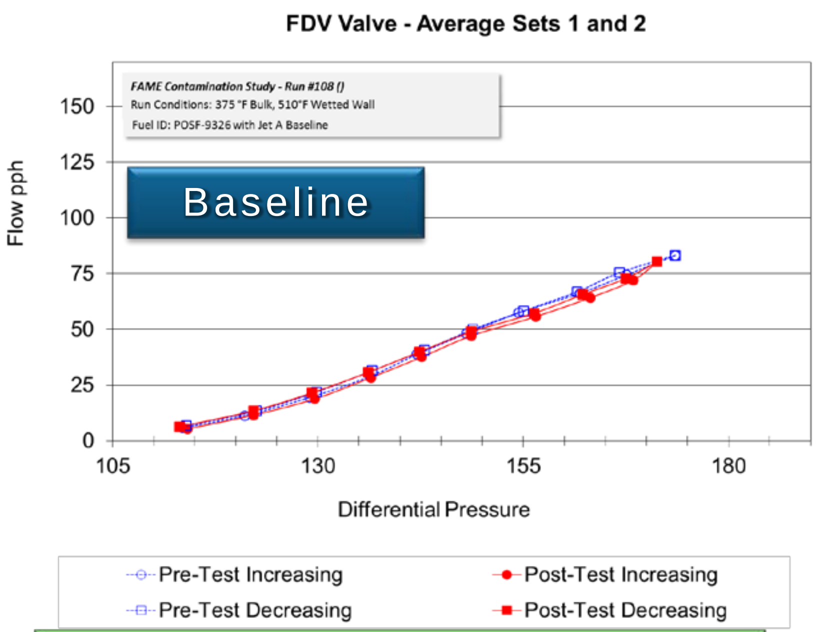
Overall Run Conditions
EDTST Mode
FAME-Sensitive Fuel
325 °F Bulk Fuel In (BFA)
375 °F Servo Bulk Fuel In
510 °F WWT (BFA)



No Negative Impact on Servo Valve Hysteresis – Perhaps even a Positive Impact(?)

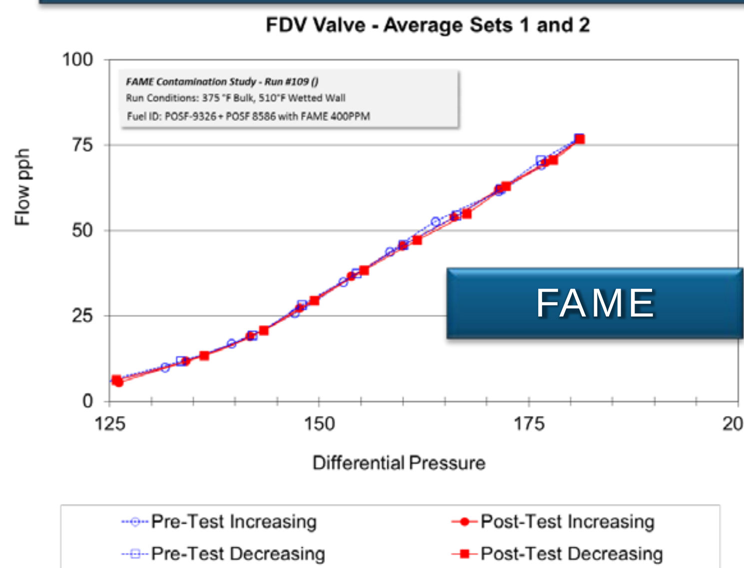
Figure H - 1 Servo Valve Hysteresis in Baseline and FAME-Contaminated FAME-Sensitive Fuel

EDTST Mode FDV Hysteresis
FAME-Sensitive Fuel



Overall Run Conditions

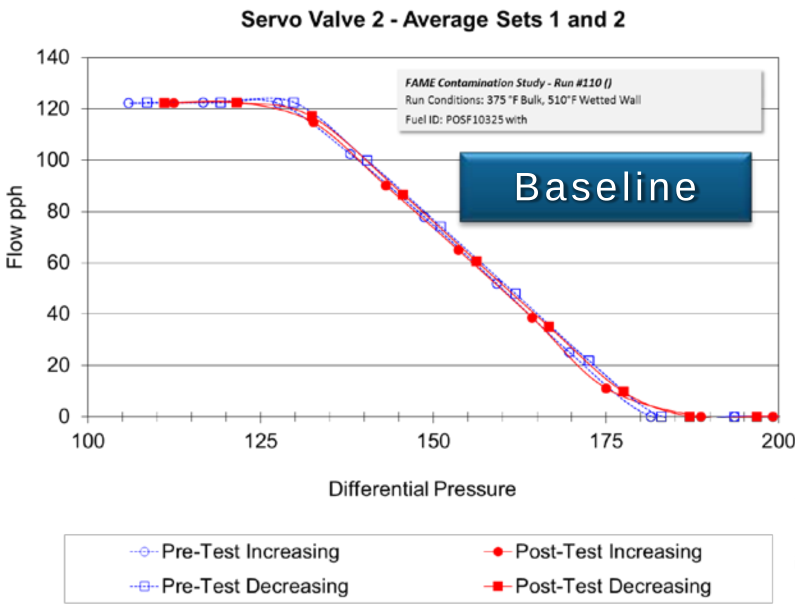
EDTST Mode
FAME-Sensitive Fuel
325 °F Bulk Fuel In (BFA)
375 °F Servo Bulk Fuel In
510 °F WWT (BFA)



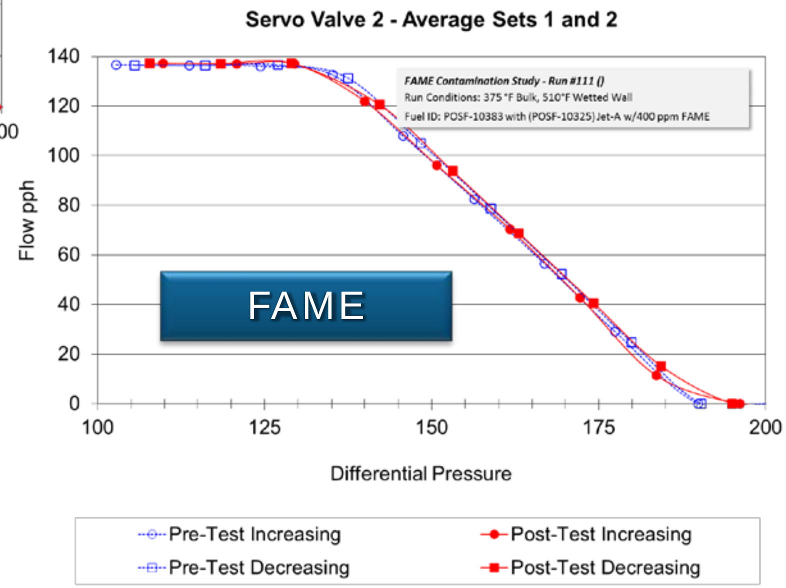
No Negative Impact on FDV Hysteresis – Perhaps even a Positive Impact(?)

Figure H - 2 FDV Hysteresis in Baseline and FAME-Contaminated FAME-Sensitive Fuel

EDTST Mode Servo Hysteresis
Typical Jet A Fuel



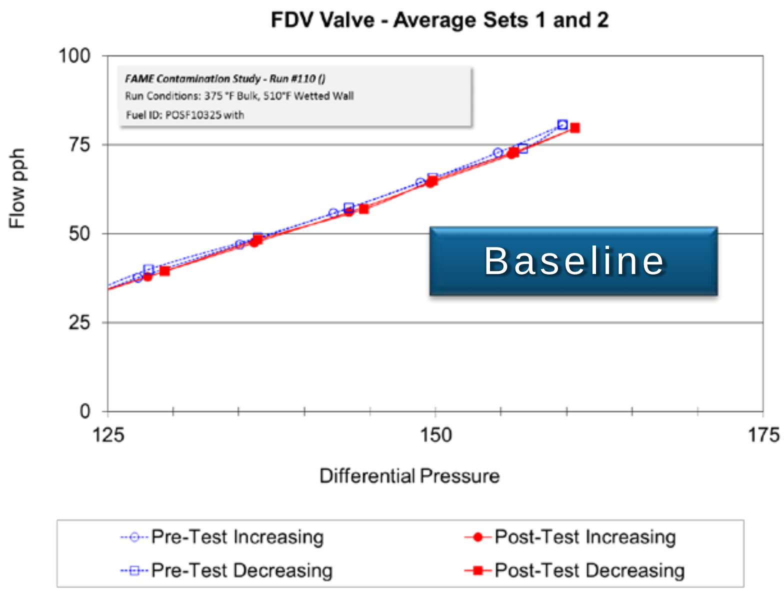
Overall Run Conditions
EDTST Mode
Typical Jet A Fuel
325 °F Bulk Fuel In (BFA)
375 °F Servo Bulk Fuel In
510 °F WWT (BFA)



No Impact on Servo Valve Hysteresis

Figure H - 3 Servo Valve Hysteresis in Baseline and FAME-Contaminated TYPICAL JET A Fuel

EDTST Mode FDV Hysteresis
Typical Jet A Fuel



Overall Run Conditions
EDTST Mode
Typical Jet A Fuel
325 °F Bulk Fuel In (BFA)
375 °F Servo Bulk Fuel In
510 °F WWT (BFA)

No Impact on FDV Hysteresis

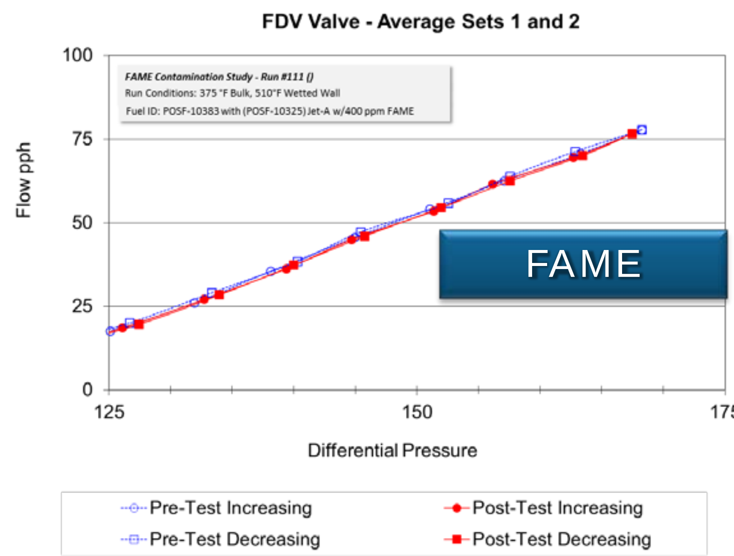


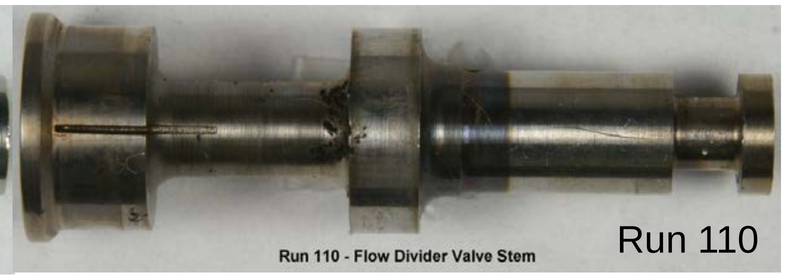
Figure H - 4 FDV Hysteresis in Baseline and FAME-Contaminated TYPICAL JET A Fuel

FDV Valve Stem Comparison

FAME-SENSITIVE FUEL (9326) JFTOT BP = 285 °C	TYPTICAL JET A FUEL (10325) JFTOT BP = 290 °C

BASELINE

BASELINE



FAME

FAME

Figure H - 5 FDV Valve Stem Deposition Comparison FAME-Sensitive vs Typical Jet A

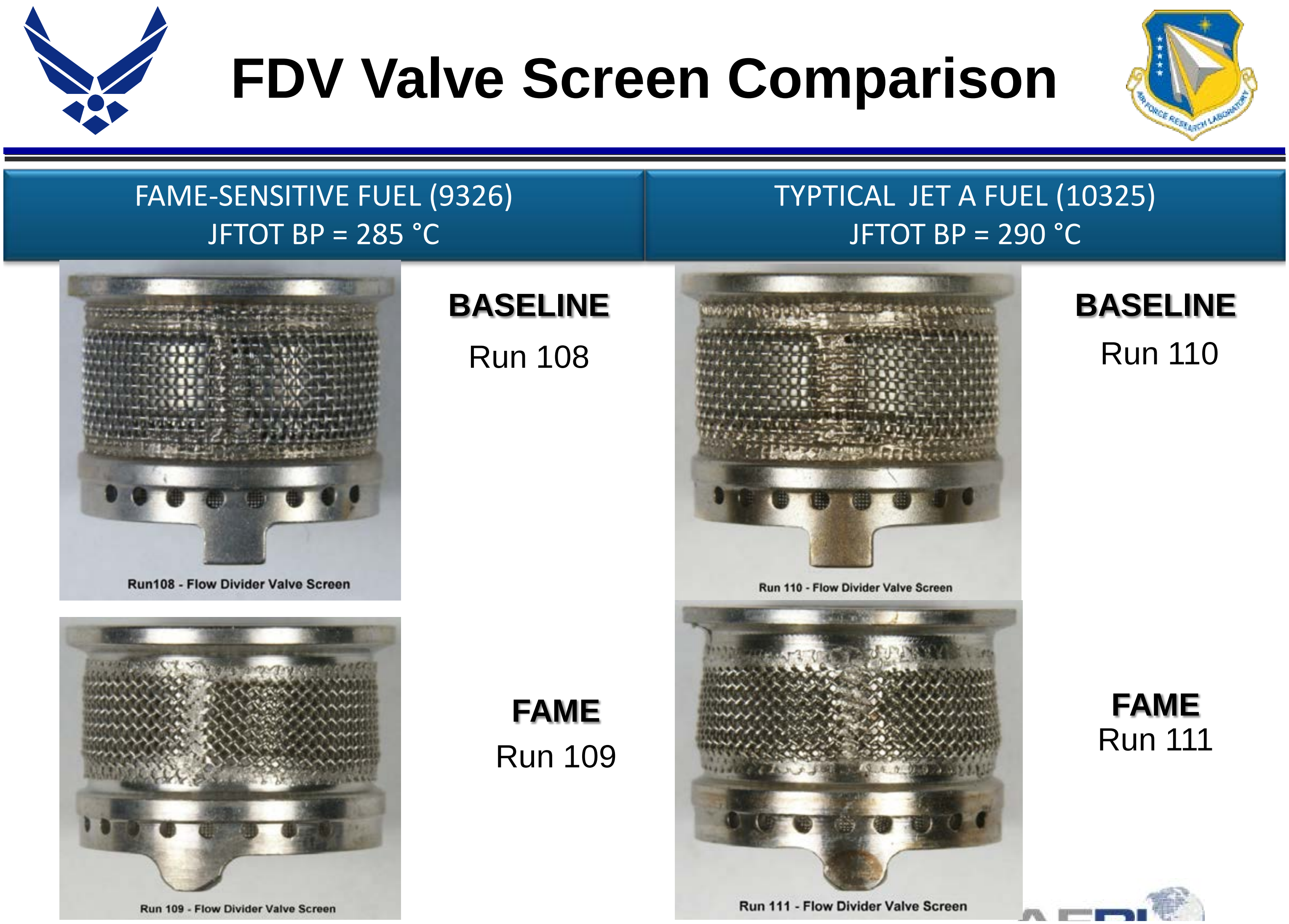


Figure H - 6 FDV Valve Screen Deposition Comparison FAME-Sensitive vs Typical Jet A

Servo Valve Spool Comparison

FAME-SENSITIVE FUEL (9326) JFTOT BP = 285 °C	TYPTICAL JET A FUEL (10325) JFTOT BP = 290 °C

BASELINE

FAME

BASELINE

FAME

Figure H - 7 Servo Valve Spool Deposition Comparison FAME-Sensitive vs Typical Jet A

Nozzle Screen Comparison

FAME-SENSITIVE FUEL (9326) JFTOT BP = 285 °C	TYPTICAL JET A FUEL (10325) JFTOT BP = 290 °C

BASELINE

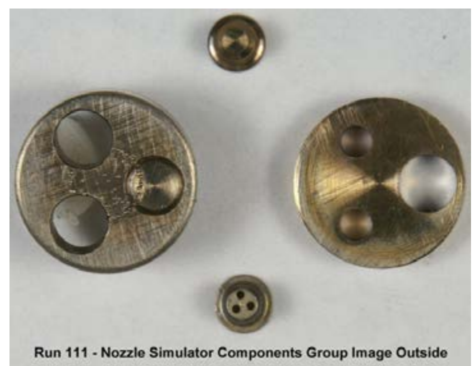
Run 108

BASELINE

Run 110

FAME

Run 109



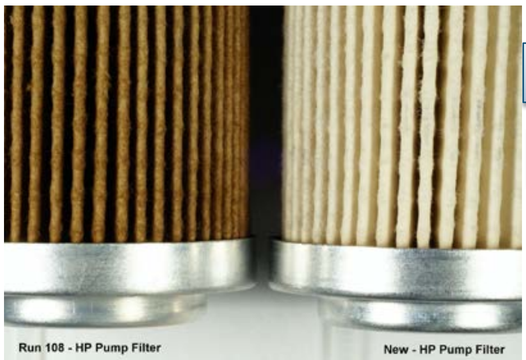
FAME

Run 111

Figure H - 8 Nozzle Screen Deposition Comparison FAME-Sensitive vs Typical Jet A

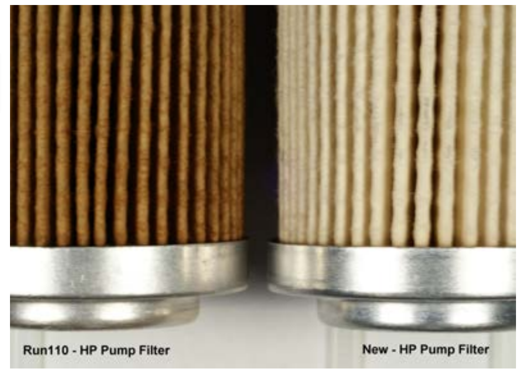
HP Pump Filter Comparison

FAME-SENSITIVE FUEL (9326) JFTOT BP = 285 °C	TYPTICAL JET A FUEL (10325) JFTOT BP = 290 °C



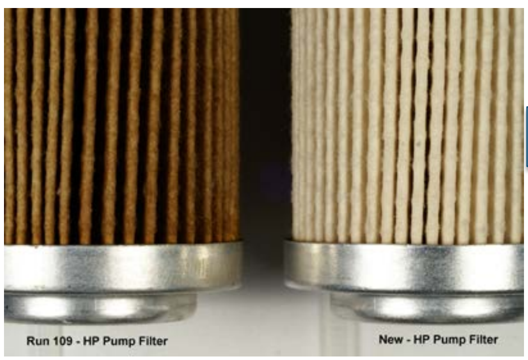
BASELINE

Run 108



BASELINE

Run 110



FAME

Run 109

FAME

Run 111

Figure H - 9 HP Pump Filter Deposition Comparison FAME-Sensitive vs Typical Jet A